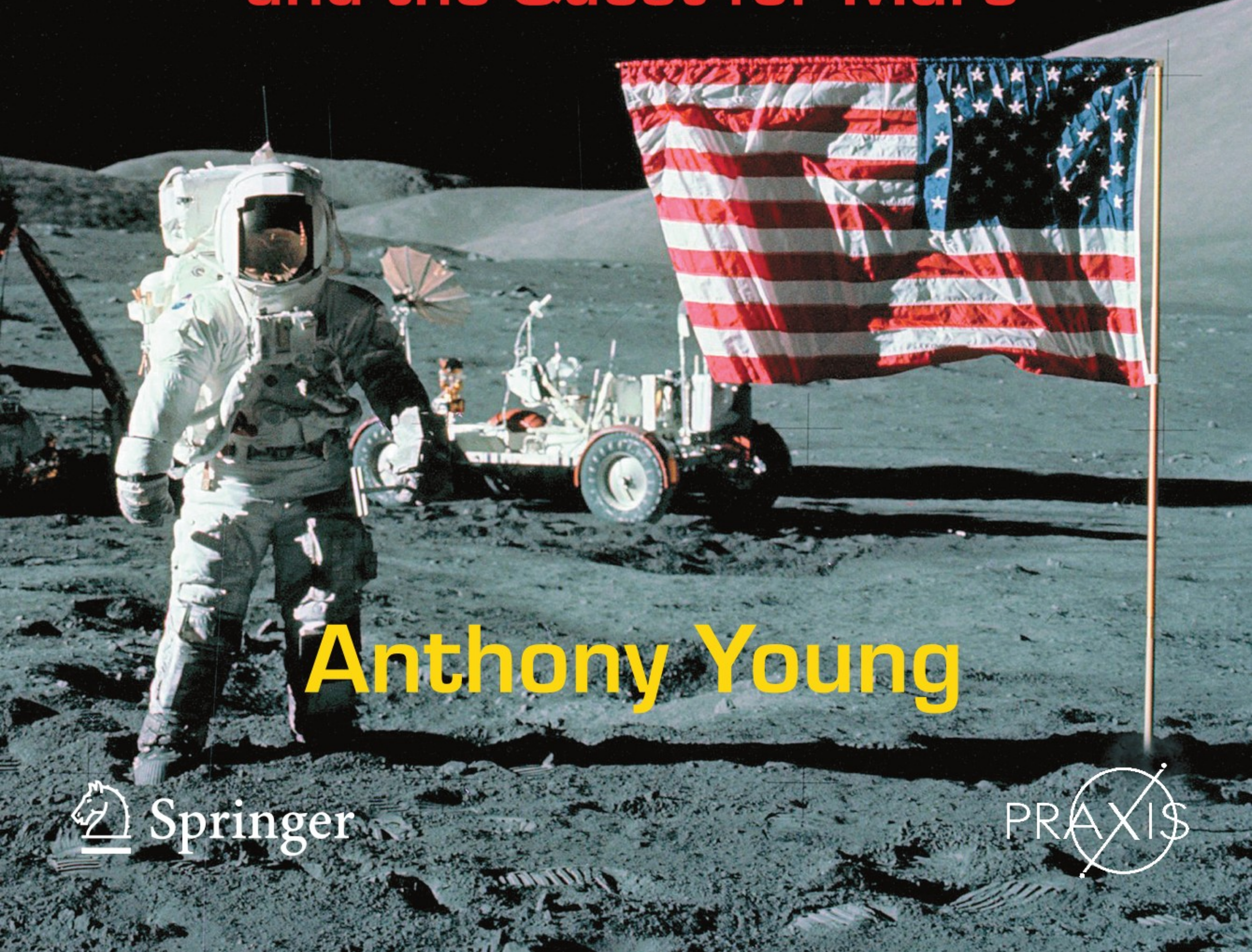
Lunar and Planetary Rovers

The Wheels of Apollo and the Quest for Mars



Anthony Young

Springer

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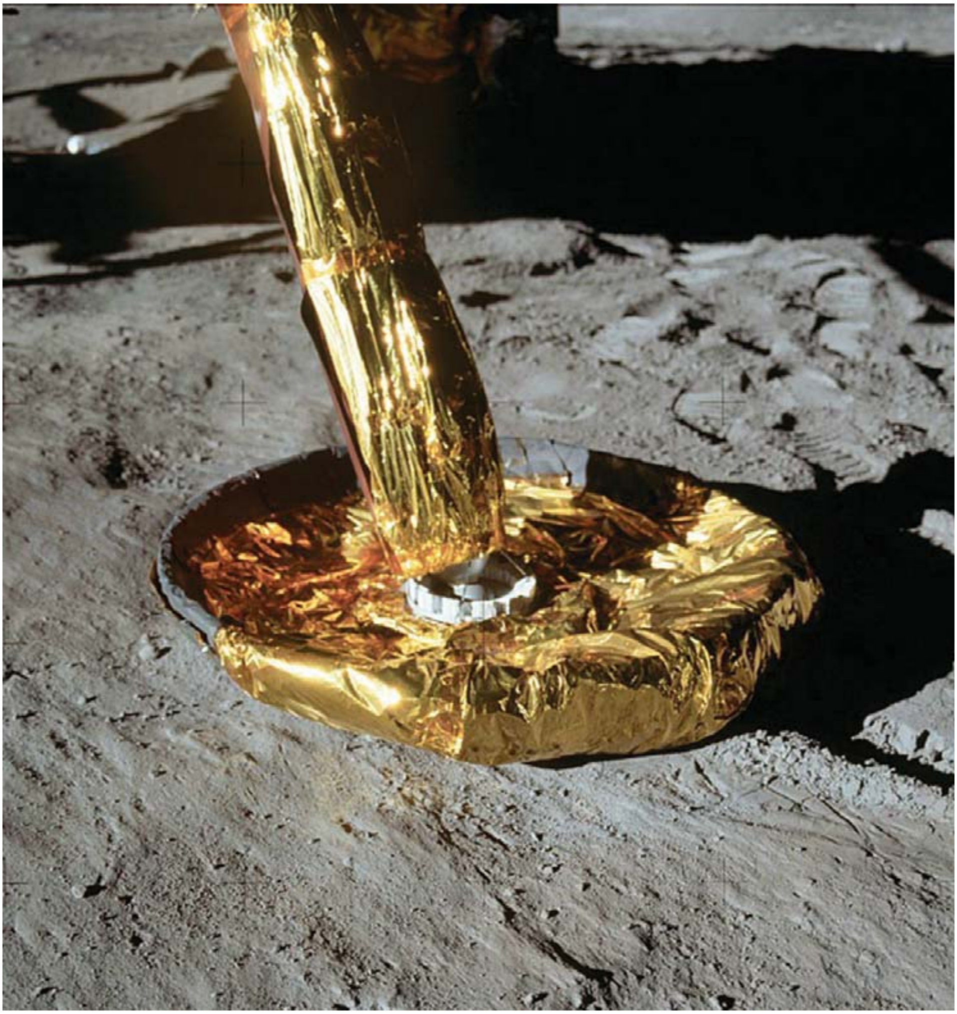

“There is nothing so far removed from us as to be beyond our reach, or so hidden that we cannot discover it.” *René Descartes*

Anthony H. Young

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The Wheels of Apollo and the Quest for Mars

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Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

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SPRINGER–PRAXIS BOOKS IN SPACE EXPLORATION
SUBJECT *ADVISORY EDITOR*: John Mason B.Sc., M.Sc., Ph.D.

ISBN 10: 0-387-30774-5 Springer Berlin Heidelberg New York

Springer is a part of Springer Science + Business Media (*springeronline.com*)

Library of Congress Control Number: 2006930590

Cover design: Jim Wilkie
Copy editing: Mike Shayler
Typesetting: BookEns Ltd, Royston, Herts., UK

Printed in Germany on acid-free paper

I dedicate this book to my daughters Erin and Katie, that they may one day experience the wonder of watching astronauts once again exploring the Moon.

Table of contents

Commander David R. Scott at Hadley Rille

Foreword

In December 1969, we had successfully completed two lunar landing missions, *Apollo 11* and *Apollo 12*. We had learned how to make a pinpoint landing at a selected site on the Moon; and we had also learned that two astronauts could conduct valuable engineering and scientific experiments on the lunar surface, including using innovative geology tools and collecting telltale rocks and regolith (soil) for detailed analysis on Earth. And we learned that the longer they could stay out on the surface, the more science they could conduct.

NASA decided that it could more than double the duration of the astronaut life support system (backpack) without major design changes. But three major barriers to efficient lunar exploration remained: (1) the distances traveled were limited by how far the crew could walk in their bulky spacesuits and heavy backpacks; (2) the amount of geology equipment (tools and cameras) was limited by what they could carry; and (3) the amount of rocks and soil collected was limited by what they could carry back to the Lunar Module (LM). Further, even though the crew could walk up to 1.5 km away from the LM, their activities could not be monitored by the TV camera posted at the LM (or they would need to carry the TV camera with them, thus reducing the amount of tools outbound and samples returned). Such monitoring by Mission Control teams (both engineering and science) could be very valuable for both safety and science.

However, even with these limitations, major scientific goals could be achieved by landing at a variety of locations on the Moon and attempting to piece together the results from each of the many missions to compile an integrated picture of the Moon. But how many different sites could be explored within the limited number of Apollo missions available? We could extend the duration of each excursion, but within the limited number of missions within the Apollo program could we satisfy our scientific objectives to understand the whole Moon? Comprehensively, with only a few missions, not really.

In December 1969, I was fortunate to be assigned the command of the planned fifth lunar landing mission, *Apollo 15*, an advanced ‘‘H’’-type mission (*Apollo 11* had been a ‘‘G’’-type mission). Having been the backup Commander on *Apollo 12*, I looked forward to the new backpack and our preliminary landing site at Davy Rille.

Jim Irwin and I would be able to double the time and distance from the LM and explore one of the most important features on the Moon, a large rille, or canyon. But we would still be limited to exploring that single geologic feature by what we could carry individually; tools out and samples back.

Four months later, in April 1970, as our training was reaching high gear, the most dramatic and hazardous halt to the program occurred: the near-loss of *Apollo 13*. After the spectacular rescue of the crew, the questions began to come: Should the program continue? Should we take any more risks? Should we terminate Apollo and be happy with our previous successes? Or should we go on? And if so, how? And how much should we try to do?

At that time, the design of a Lunar Roving Vehicle (LRV) had commenced, but the program was in serious trouble. It was behind schedule, over budget, and not satisfying its basic requirements. By June 1970, two months after the near-loss of the *Apollo 13* crew, termination of the program was being seriously considered.

But then, two months later, in August 1970, NASA made one of its boldest decisions. In the face of the near disaster of *Apollo 13*, dwindling public support, and a rapidly declining budget, NASA decided to skip the final "H"-type mission; press on with upgrading the total "system" (hardware, software, science, and operations) to the "J" configuration, and launch *three* full-up "J" missions to the most significant scientific sites on the Moon. This upgrade from "H" to "J" included, in particular, a full commitment to the LRV. This meant significantly more exploration capability, especially the capability to range to several different geologic areas from the Lunar Module; significantly more scientific equipment and experiments; and quite importantly, a mobile TV camera to view and record the distant activities of the crew. As a result, using a rover to explore multiple geologic areas at one landing site became almost equivalent to exploring multiple landing sites without a rover.

To go beyond the *Apollo 11* "G" mission demonstrated considerable courage and confidence, especially after achieving the political objective of "landing a man on the Moon and returning him safely to Earth." But to advance beyond "H" into even *one* "J" mission (much less *three* J missions), fully seven months before the recovery from *Apollo 13* and the launch of the *Apollo 14* "H" mission, required a very bold and aggressive decision. But this commitment to the extended scientific exploration "J" missions was surely one of the most rewarding decisions of the Apollo Program. It would have been a lot easier, safer, and cheaper to finish the program with the final two "H" missions as scheduled (for if one of the final missions were to be a failure, the Program would surely end, and "Apollo" would forever have been considered a "failure"). This major decision was as fortunate for the overall results and success of Apollo as it was for the inclusion of a Lunar Roving Vehicle – that one final element in the overall configuration of a complete "system" for human planetary exploration. For the future of Apollo and for human planetary exploration in general, the bosses truly made the "right" decision!

For our mission on *Apollo 15* (as well as *16* and *17*), the shift to a "J" mission and the inclusion of the LRV meant that we would cover seven times the distance covered on "H" missions. We would travel almost four times the distance from the LM, we would be able to carry many more tools, and we could collect and return twice the

amount of surface rocks and soil. Further, because of the mobility of the LRV, we would be able to explore three different geological areas at our landing site, from a rille, to large craters, to the mountains; a true boon to the scientific exploration and comprehensive understanding of the whole Moon.

This book thoroughly describes one of the major the results of that bold decision, for both engineering and science. However, the real significance of this story may very well be its value to future planetary explorers, including robotic explorers, and even "virtual" explorers. When these future explorers look back, they will surely ask: what did we learn from Apollo? How does it apply to the future? When will such an adventure happen again?

When will we go again – to explore first-hand the Moon, Mars, or another planet? Or perhaps more specifically, when will *humans* ever again walk, and rove, on another planet? One could argue that even the current status of "robotic technology" precludes the need to risk the life and cost of humans *in situ* exploring the surface of an extra-terrestrial body. The remarkable advances in computer science and robotics, including software that produces human-like capabilities, seem to indicate that it will not be long before many will say that artificially-intelligent robots of the future should replace the artificially-robotic humans of the past (picture those somewhat-intelligent Apollo beings of the mid-twentieth century in those old stiff, bulky, heavy pressure suits!). But will robots ever be able to experience the high adventure of exploring the unknown sights of a new frontier? Not really.

The Lunar Roving Vehicle was the final element in the fundamental configuration for human planetary exploration – a planetary lander, a life support system, a surface rover, and a recovery spacecraft for return to Earth. All future human exploration "systems" will surely include these four basic elements, in one form or another. The Apollo LRV was the first of the manned surface rovers in this enduring configuration. The following chapters tell its story: for history, for research, and as the basis for defining future planetary expeditions, wherever they may go. And wherever they may go, a planetary rover will most likely be along, a planetary rover basically the same as the one described in this exceptional book.

David R. Scott
Los Angeles
June 2006

Author's Preface

This book began with the goal of writing about the design, development, testing and building of the Lunar Roving Vehicle, and the experiences of the astronauts who used the LRV during Apollo 15, 16 and 17. When quoting Apollo astronauts David Scott, John Young, Charlie Duke, Eugene Cernan and Harrison Schmitt from my interviews with them, I refer to my interview to distinguish from quoted material from the Apollo mission transcripts or other taped or written material. I also made this distinction with other individuals I interviewed for this book.

During peer reviews of the book proposal, it was suggested I tie in the tremendous successes of the Martian rovers *Sojourner, Spirit* and *Opportunity* as part of the book subject matter. This made sense, but it became clear I would not be able to devote as much space or detail to these rovers as I had for the Lunar Roving Vehicle. I have devoted a chapter to these amazing machines and the Mars Science Laboratory as an overview, since the Mars Pathfinder mission and the Mars Exploration Rovers have already been the subjects of separate books by the JPL engineers and scientists directly involved with them. These are listed in the bibliography.

When the Vision for Space Exploration (VSE) was announced by President George W. Bush in January 2004 at NASA headquarters, the space agency made a dramatic shift in its human space exploration plans and goals, proposing a return to the Moon and eventual crewed missions to Mars. The U.S. Congress supported this new initiative, if modestly. It appeared that the United States, along with its international partners, would indeed return to the Moon with the distant goal of human missions to Mars. It was obvious that future lunar crews would need rovers. The VSE is a reality and not a grandiose proposal. I wanted to explain the numerous previous attempts at proposing America's return to the Moon, and beyond, why those space exploration proposals failed, why the VSE succeeded, and what the future holds for both manned and robotic rovers.

There were numerous suggestions to devote a chapter to the Soviet Lunokhod rover program. The more I looked into it, the more I realized I would not have the time to conduct the necessary research or interviews. Fortunately, Ron Creel, who has helped me so much with this book, agreed to make a written contribution. Ron was a thermal control engineer on the Lunar Roving Vehicle, and is very

knowledgeable about the Lunokhod rovers, having met and shared information with the engineers in Russia who worked on the program. His summary of the Lunokhods and the challenges they conquered appears in the Appendix.

It is my hope this book will add to the body of knowledge regarding lunar and planetary rovers. The lessons of history are a priceless resource that can be used in designing the rovers of the future.

Anthony Young
May 2006

Acknowledgements

This book had its genesis in an article I wrote for *Automobile Quarterly*, titled **LRV: Apollo's Wheels on the Moon** and published in Vol. 43, No. 4 (Fourth Quarter, 2003). I want to thank Managing Editor Tracy Powell for giving me the green light to write it. I uncovered so much information, I realized there was a possible book.

I want to thank the Apollo astronauts who drove and rode the Lunar Roving Vehicle for the interviews for that article and this book. Much of what they told me could not fit into the article, but now appears here. Fellow Praxis author David Harland arranged the interview with David R. Scott, Commander of Apollo 15. David Scott afforded me many new insights into the mission planning, training and the wonders of the Hadley Apennine region that he explored. Apollo 16 Commander Capt. John Young managed to find time in his still busy schedule at the Manned Spacecraft Center to recall his experiences on the Descartes Highlands with the rover, and what America should do when it returns to the Moon. His crewmate, Charles "Charlie" Duke spoke to me at length about their heart-pounding landing, the discoveries at Descartes in general and some of the quirks of trying to ride on the rover in $\frac{1}{6}$-G. Capt. Eugene Cernan, certainly one of the busiest of the Apollo astronauts, carved out a precious slot of time to regale me with his massif-dodging landing at Taurus-Littrow and how the rover vastly expanded their capability to explore the Moon. No less busy was Dr. Harrison H. Schmitt, who was Capt. Cernan's Lunar Module Pilot on Apollo 17. Dr. Schmitt reviewed Chapter 3 on training. Jim Irwin, Lunar Module Pilot on Apollo 15, passed away in 1991, but his book *To Rule the Night* provided his viewpoint on the wondrous experience Apollo 15 was for him.

I began my research for this book at the University of Alabama in Huntsville. Anne Coleman, in charge of the Archives & Special Collections at the M. Louis Salmon Library at the university, made available to me the entire collected papers of Saverio "Sonny" Morea, who was manager of the Lunar Roving Vehicle program at the Marshall Space Flight Center. Those papers, collected in nearly twenty binders, were meticulously organized by Ms. Coleman's able archive assistant, Nikki, who also established the online Lunar Roving Vehicle (LRV) Database. This information was priceless in establishing the chronological events of the LRV program. Mike

Wright, historian at the George C. Marshall Space Flight Center, helped me to gather information and photos.

I want to thank Sonny Morea for my original interview with him in 2003 and his willingness to follow up with information when the book project started. Ronald A. Creel, who was a key principal thermal control engineer on the LRV, not only gave me a wealth of information on the LRV, he scrupulously proofed every chapter for accuracy. His help was invaluable. I would also like to thank Otha "Skeet" Vaughn for giving me the details of the lunar soil studies and LRV wheel tests he was involved in. Jim Sisson reviewed my chapters on the Apollo "J" missions and gave me some personal insights that appear in the book. I was most fortunate to speak with Sam Romano who was a pivotal individual in the LRV's history and development. One of Romano's senior engineers, Ferenc Pavlics, spoke to me at length about the LRV development work at General Motors in California. Eugene Cowart was Boeing's LRV program chief engineer in Huntsville and he gave me his insights and some rare literature. Sam Russell and Ed Fendell spoke to me about the design and operation of the Ground-Commanded Television Assembly. Don McMillan is credited with the 3-D computer model of the LRV you see in this book. Jeff Foust, editor of *The Space Review* website, was a referee of my book proposal, as were several others.

Geologists Dr. Gordon Swann, Dr. William Muehlberger and Dr. Gerald "Jerry" Schaber were most generous with their time to tell me of their work with the astronauts in their training and mission planning for Apollo 15, 16 and 17. Jerry Schaber in particular offered me his comprehensive document on USGS history during the Apollo program, which you can learn more about in the Bibliography.

For Chapter 7, I would like to thank Andrew Mishkin at the Jet Propulsion Laboratory in Pasadena, California for his input and proofing of the chapter. Frank Delgado at the Johnson Space Center in Houston, Texas offered insight on the next generation of rover technologies as part of the new Vision for Space Exploration.

Eric Jones is known the world over as the father of the Apollo Lunar Surface Journal. Eric and his contributors have made this online resource the finest of its kind. Eric was most helpful to answer any question I might have, and the voice transcripts of Apollo 15, 16 and 17 were taken from the ALSJ.

Finally, I would like to thank Dr. Hans Koelsch at Springer for first considering my book proposal and then sending it on to Clive Horwood at Praxis Publishing Ltd. in England. It has been gratifying to work with Mr. Horwood to produce the book you hold in your hands.

List of Illustrations

Frontispiece

Training for the Moon

Color Section 1

Destiny at Taurus-Littrow

Color Section 2

Dr. Wernher von Braun became the first director of NASA's Marshall Space Flight Center in Huntsville, Alabama in 1960. He oversaw such massive engineering programs as the development of the Saturn I and Saturn V launch vehicles, as well as lunar vehicle studies from the Mobility Test Articles (MTA) to the Lunar Roving Vehicle (LRV). Here, von Braun points out the zoom lens of the TV camera to be used on the LRV. (NASA/MSFC)

From concept to reality

In the midst of Project Gemini in 1965, Dr. Wernher von Braun, the first Director of the Marshall Space Flight Center (MSFC), arranged an impromptu meeting with some of the astronauts. Most of them had yet to fly into space. The astronauts were among the third group selected by NASA in October of 1963 for Gemini and the upcoming Apollo program. One of the astronauts sitting across from Dr. von Braun was Capt. Eugene Cernan, who was training for his upcoming Gemini IX flight the following year. It was just an informal meeting, but von Braun knew some of the men he was looking at would one day walk on the Moon. The famous rocket scientist had even bigger plans for the astronauts who would eventually realize the long-held dream of traveling to and landing on the Moon. It was at this meeting that the astronauts learned what Dr. von Braun really had in mind.

"There were six to eight of us at this table," Cernan recalled in an interview with this author. "The thing I remember specifically was von Braun saying, 'Don't you worry about getting to the Moon. I will get you there. It's what you do when you get there that's important.' And that's when he said, 'You will probably be driving a car on the Moon.' That was almost as far-fetched then as going to the Moon itself. At that time, people were looking at rocket boots and other means of getting around in $\frac{1}{6}$ gravity. We're talking about a bunch of men in the program at that point in time who had never even flown. Going to the Moon was still a long way off, and he was talking about driving cars a quarter of a million miles away."

Making such confident predictions was something von Braun was quite at home doing. He had been doing it for many years. Von Braun needs no introduction, but what is perhaps little known was his consummate skill in harnessing the mass media to promote his vision of space exploration. Whether it was the series of articles for *Life* and *Collier's* magazines during the 1950s, or the Walt Disney TV specials that captivated millions of Americans in their living rooms with the real possibility of exploring first the Moon and then the solar system, von Braun proved to be a most articulate spokesman. Yet he spoke in a language the average man, woman and child could understand. Von Braun was a visionary, but a visionary with a plan backed up by hard science. He realized he was at the threshold of technology that could truly make it possible, and he used every opportunity to speak not only of the romance of

space exploration, but also of its benefits to mankind. He knew that if he could harness the public's imagination and support for American efforts in space, Washington would loosen the purse strings.

Von Braun knew that once man reached the Moon, he would eventually need some means of traveling about on its surface. The idea was not new. Jerszy Zulawski depicted a rover in his science fiction novel, *A Srebyym Globie,* published in 1901. In 1915, American writer Hugo Gernsback described a Lunar Rover in *Baron Munchausen's New Scientific Adventures*, though this was a sphere with a circumferential track. Numerous other rover ideas appeared in the magazine and book press during the 1920s and 1930s, but perhaps the most prophetic Lunar Rover description to appear in print came from Arthur C. Clarke. In 1951 he published *The Exploration of Space*, in which he wrote: "Pressurized vehicles with large balloon tyres would also be employed for much of the same duties that they fulfill on Earth. Their motors would be electric, operated by storage batteries, or else turbines, driven by reacting rocket fuels, either directly as in a gas turbine or indirectly through the use of some intermediate fluid." Von Braun, acting as a contributor to the book *The Conquest of the Moon* published in 1953, described a tracked lunar vehicle powered by turbines. However, it would take a geopolitical event to move the hope of even getting to the Moon from a dream to eventual reality. When the Russians launched the first satellite in 1957, von Braun saw the event not as a threat, but an opportunity.

SPUTNIK AND PROJECT HORIZON

Few events in the twentieth century had as profound an effect on America as did the successful launch and orbit of Sputnik I on 4 October 1957. The ideological enemy of the United States, the Soviet Union, had beaten America into space. The Cold War that existed between the two countries now came into millions of American homes as TV broadcasts described the stunning success of Sputnik. A new phrase entered the American lexicon: "space race." In response, Congress passed legislation forming the National Aeronautics and Space Administration – NASA – in 1958. This new agency was distinctly civilian. However, the U.S. military saw a far greater threat in Sputnik and the subsequent Soviet launches, despite the fact that some publicly downplayed their significance. Von Braun stated that Sputnik had no inherent military significance, but it held tremendous import as being the first thrust into outer space and it had been achieved by a communist nation. When the U.S. launch of Vanguard failed, von Braun, then at the U.S. Army Ballistic Missile Agency, was handed the task of matching or surpassing the Soviet achievement. His team succeeded in doing that when Explorer I was launched on 31 January 1958 from Cape Canaveral, Florida.

What von Braun could not reveal was the start of a secret U.S. Army space program titled Project HORIZON. By 1959, the U.S. Army had prepared the Project HORIZON Report, which called for the establishment of a lunar military outpost that could sustain ten to twenty personnel. In defining the requirement, the report

stated: "The establishment of a manned base of operations on the Moon has tremendous military and scientific potential. Because invaluable scientific, military, and political prestige will come to the nation that first establishes a lunar base, it is imperative that the United States be first." In emphasizing the sense of urgency regarding the achievement of that goal, the report stated: "To be second to the Soviet Union in establishing an outpost on the Moon would be disastrous to our nation's prestige and in turn to our democratic philosophy." Project HORIZON would require a level of effort unprecedented in the history of the U.S. Army in terms of development. This included heavy-lift boosters, space vehicles, intermediate space stations, space and lunar dwellings, space suits, special consumable supplies and many other requirements. The first manned landings were to take place in 1965 and it was expected to have an operational base by late 1966.

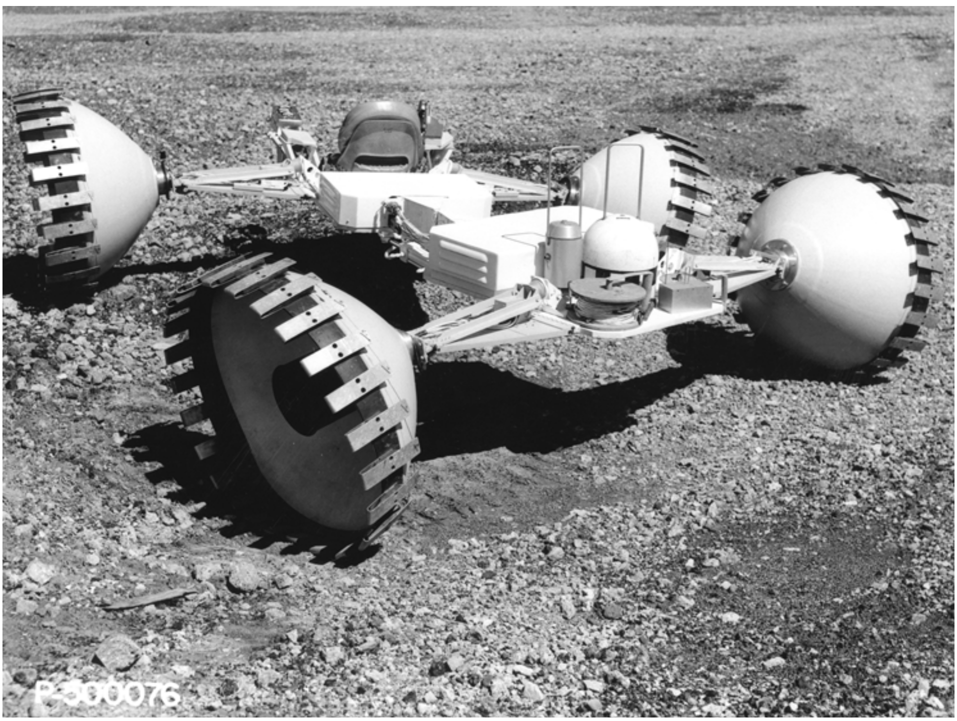
The program called for the creation of the Saturn I, already under development by the Advanced Research Projects Agency (ARPA) and the Army Ballistic Missile Agency, ostensibly von Braun's group. It would be supplemented by an up-rated version, the Saturn II. The HORIZON report required sixty-one Saturn I launches and eighty-eight Saturn II launches through November 1966. It was estimated that the entire cost of the eight and one-half year program would run to six billion dollars. The authors of the report were quick to point out that this worked out to less than two per cent of the annual defense budget at that time. To say Project HORIZON was ambitious is an understatement. Of course it was never implemented, but key elements of it certainly were, in Project Apollo that followed. Perhaps the greatest contribution Project HORIZON made to the U.S. space program was the development of the Saturn I and the subsequent research and development that helped to define the Saturn V. The early development of the Saturn I made it possible for President John Kennedy to make his stirring speech on 25 May 1961 before Congress and the American people, of landing an American astronaut on the Moon before the decade was out and returning him safely to Earth. Project Apollo, in a civilian sense, was the heir of Project HORIZON. The first Saturn I launch took place on 27 October 1961. It proved the clustered engine concept and contributed to the rocket's superb reliability. This was ably demonstrated throughout the 1960s with all the launches of the Saturn I and Saturn I-B.

LUNAR MOBILITY STUDIES AT MARSHALL SPACE FLIGHT CENTER

MSFC had been conducting lunar mobility studies since the early 1960s. The first of these was the Lunar Logistics System (LLS), followed by the Mobility Laboratory (MOLAB), then the Lunar Scientific Survey Module (LSSM) and the Mobility Test Article (MTA). They were based on the premise of a dual-launch scenario using two Saturn Vs, one to deliver the crew to lunar orbit and the lunar surface and the other to carry all the equipment to sustain and transport the crew while they were there. The LLS, begun in the fall of 1962, involved studies by the Grumman Aircraft Engineering Corp. and Northrop Space Laboratories Inc. Many of the large

aerospace firms involved in the design and engineering of various segments of the Saturn V would also be involved in concepts and working prototypes for Lunar Rover studies. The LLS studies produced by Grumman and Northrop were among the first produced for MSFC and laid the groundwork for subsequent studies. These were pressurized cabin vehicle designs, using electrical power for each wheel.

Dr. Mieczyslaw G. Bekker was an authority on land locomotion during the late 1950s and the 1960s. Much of his pioneering work was conducted at the General Motors Defense Research Laboratories (GMDRL) in Santa Barbara, California. Bekker was head of the Mobility Research Laboratory there, and Samuel Romano was chief of Lunar and Planetary Programs. In May 1963, Dr. Bekker and Ferenc Pavlics released Staff Paper SP63-205, titled "*Lunar Roving Vehicle Concept: A Case Study*." This paper was prepared in conjunction with a GMDRL study contract for an unmanned roving vehicle for the JPL/NASA Surveyor Spacecraft program. The original wire frame wheel concept was developed for this rover with the cooperation of Goodyear Tire and Rubber Co. The paper described a six-wheeled articulated vehicle, with its wheels connected to each other by flexible rods. This gave the vehicle an elastic-like frame that permitted each of the three axles to move independently of each other. Each wheel was driven by a $\frac{1}{15}$ horsepower DC electric motor powered



MSFC explored a number of different configurations of the MTAs during the 1960s. This MTA from 1965 was a single-seat design with an articulated chassis, built by Grumman. (NASA/MSFC)

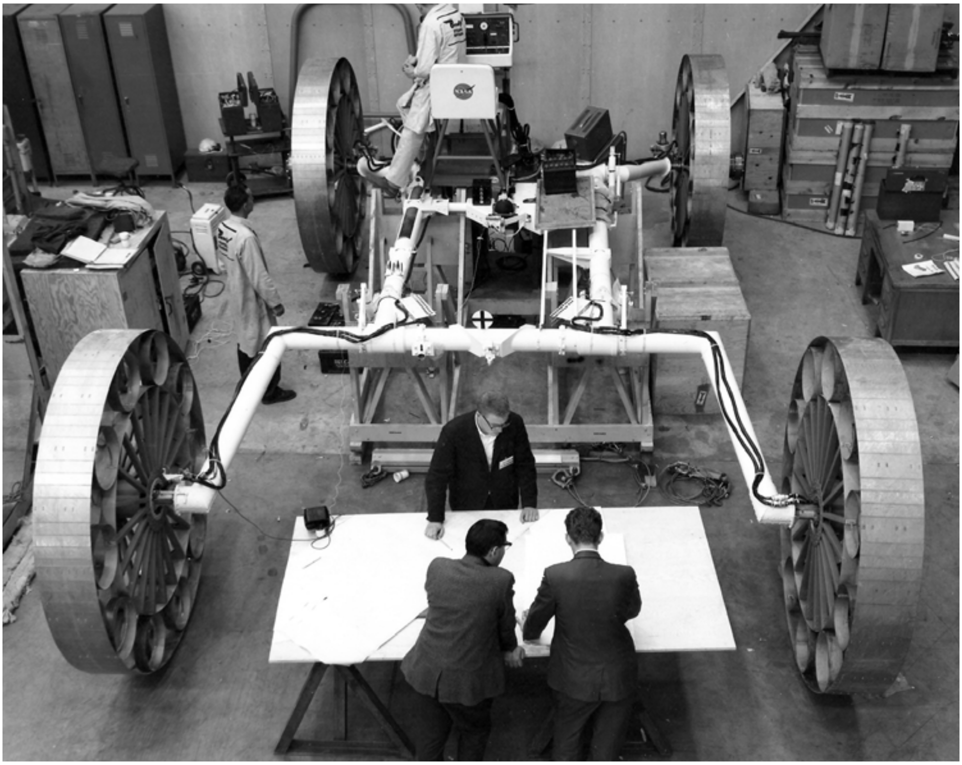
by silver-cadmium batteries. The vehicle measured 366 cm long by 152 cm wide, with each wheel measuring 92 cm in diameter and 38 cm wide. The gross weight of the vehicle was kept to roughly 30 kg to simulate a 182 kg vehicle on the lunar surface. This was a robotic vehicle and was designed to test a number of concepts. It proved amazingly adept at scaling seemingly impossible obstacles.

Grumman and Northrop were not the only aerospace corporations involved with lunar vehicle studies. Bendix Corporation began such studies in 1960 as part of the company's long-term interests, and they would invest heavily in the design and development of lunar transportation systems. Boeing Aircraft Corporation also began such studies at this time. In February 1964, P.J. deFries, director of the Systems Concepts Planning Office at MSFC, reviewed the ongoing lunar vehicle design work by both companies to determine their capabilities for lunar vehicle hardware development. The following month, a Request for Proposals (RFP) was issued by MSFC as part of the forthcoming Apollo Logistics Support System (ALSS). Proposals from Bendix, Boeing, Chrysler, General Electric and Grumman for a preliminary design study were submitted to MSFC in April 1964.

Then in June, Boeing (with GMDRL as the vehicle technology subcontractor) and Bendix received contracts from MSFC with identical mission requirements, to initiate studies and build prototypes for the Mobility Laboratory (MOLAB) program. This was conceived to hold a crew of up to four men within a pressurized vehicle for longer traverses of several days to two weeks. The Bendix design was approximately 9 m in length and weighed 3,060 kg. It was a four-wheeled design and was capable of a range of 90 km. The Boeing-GMDRL design was 11.5 m in length, and consisted of a four-wheeled pressurized vehicle which towed a two-wheeled rear section for scientific tools and instruments, with a cargo area for lunar samples. It weighed approximately 3,600 kg and had a greater range than the Bendix design. Significant in the Boeing design was the use of woven wire wheels and electric motors to drive each individual wheel. These wheels were developed by GMDRL during the early Lunar Rover programs, and Ferenc Pavlics and his team would later receive a patent for them in 1969.

Several crucial design elements had already been chosen by 1964. Metal wheels were preferred to track-laying concepts because they consumed less power, were less complex, and were not as sensitive to temperature extremes, among other advantages. Electric motors were chosen as the means of propulsion, but significantly, each wheel would be driven by an individual motor. Initially, it was thought that hydrogen-oxygen fuel cells would be the means of providing electrical power to the motors, but these would ultimately give way to relatively conventional batteries. Vehicle steering would be achieved using two levers instead of a traditional steering wheel. This, too, would eventually be refined considerably. However, in November 1964, NASA Associate Administrator, Dr. Robert Seamans, announced general post-Apollo plans that effectively shelved the ALSS (including MOLAB) until after 1975, in favor of a less ambitious approach.

A follow-up contract was issued to both the Boeing team and Bendix after the MOLAB program, for the Lunar Scientific Surface Module (LSSM). Von Braun referred to this vehicle as a "lunar jeep." It was an open vehicle designed to carry two



The Bendix Corporation MTA is shown nearing completion. The company took a unique approach to wheel design that would absorb shocks through the use of steel hoops within the outer body of the flat steel wheel, with square section steel tubing giving the wheel rigidity. (NASA/MSFC)

astronauts, or one astronaut with added cargo capability. The astronauts would drive this vehicle wearing their suits and Personal Life Support System (PLSS). It had a roll cage to protect them in the event of a rollover and it would be equipped with a dish-type communication antenna. The LSSM was designed to be mounted to the Lunar Module Shelter during its descent to the Moon – one concept being considered – and would then be lowered to the lunar surface by the astronauts after landing. A mockup of the LSSM was built and demonstration trials performed, powered by conventional batteries and using pneumatic tires.

As a precursor to the LSSM, Marshall Space Flight Center also looked into unmanned robotic rovers which could be controlled from Earth. Simulators were built and tested incorporating the actual time delay of several seconds between getting a visual image from the rover on the Moon to the Earth, and then sending the steering command back to the rover. Von Braun was a supporter of the unmanned robotic Lunar Rover and felt it could be a tremendous aid to properly establishing the actual geologic conditions for a considerable area around prospective landing

sites. It was also studied as a vehicle for astronauts to use for exploring areas too dangerous for them to enter themselves.

Yet another vehicle concept was the Lunar Mission Development Vehicle (LMDV). This was designed and constructed by GM's AC Electronics-Defense Research Laboratories under the management of Sam Romano for a 1964-1965 NASA contract. Romano had joined General Motors in Detroit, Michigan in 1960 in charge of Special Vehicle Development in their Defense Systems Division. In 1961, GM moved the division to Santa Barbara, California as the Defense Research Laboratories and Romano became manager of Lunar and Planetary Programs. The LMDV was a fully-enclosed articulated vehicle incorporating a number of features described in Bekker's 1963 paper. It was designed for use by the Astrogeology Branch of the U.S. Geologic Survey in order to develop methods, exploration procedures and surface equipment for lunar exploration. It was identified on the side as the Mobile Geologic Laboratory. The LMDV measured 5.2 m long, featured 137 cm pneumatic tires, had a top speed of 40 kph and weighed 2,272 kg. It was powered by a horizontally opposed four cylinder gasoline engine.

As a later study, vehicles called Mobility Test Articles (MTA) were built to test propulsion concepts and wheel configurations. These were constructed under NASA contract between 1965 and 1966. The MTAs were open test vehicles with no body, only the chassis and wheels, with drivers out in the open.

Clearly, Marshall Space Flight Center was looking for the optimum vehicles to have for future lunar programs, but they were not confined to surface transportation. The Marshall Center also looked at flying vehicles. The primary contractor looking into these concepts was Bell Aerospace Systems. Bell built two flying prototypes; one was the one-man rocket belt design which was actually depicted in the James Bond movie *Thunderball* (1965). This design was fully capable in 1-G on Earth, and on the lunar surface its fuel consumption would be $\frac{1}{6}$ that on Earth. There was also a larger version, still employing one man to fly it, but with a frame that permitted the astronaut to sit during flight.

Von Braun wrote constantly on the various aspects of space flight and launch vehicles. In the early 1960s, he began to write a series of articles for *Popular Science* magazine on space exploration in general and on America's future efforts in particular. His article, "*Dr. Wernher von Braun tells How We'll Travel on the Moon*," appeared in the February 1964 issue. In it, von Braun revealed that studies had been underway at Marshall Space Flight Center in conjunction with Lockheed, Bendix, Boeing, General Motors, Brown Engineering, Grumman and Bell Aerospace systems. Von Braun wrote in particular: "For short distance travel, a non-pressurized 'moon jeep' may suffice. The astronauts would hop onto its open platform and depend for protection upon their pressurized space suits, while life support and communication would be provided by their backpacks." The subjects von Braun wrote of and had published in mass-circulation magazines were for public education, but were based not only on the studies conducted at MSFC but also on formal policies developed at scientific conferences held at the time. It was at these conferences that the scientific community outside of NASA could offer its input as to the goals, specific experiments and desired equipment that should go into missions

In this photo taken in June 1966, MSFC Director Dr. Wernher von Braun drives a Mobility Test Article (MTA) built by the Bendix Corporation. Data provided by the MTAs helped in the eventual design of the LRV. (NASA/MSFC)

being planned for Apollo. Geologic training of the astronauts was already underway (see Chapter 2), but hardware to be used on the lunar surface was still being established. The need for a Lunar Roving Vehicle to aid Apollo crews on the Moon formally came out of these conference discussions.

THE LUNAR EXPLORATION AND SCIENCE CONFERENCES OF 1965 AND 1967

In July 1965, NASA's Manned Space Science Coordinating Committee sponsored a conference in Falmouth, Massachusetts. Lasting two weeks, the *Summer Conference on Lunar Exploration and Science* was convened to map out a ten-year program of lunar exploration, with the emphasis on manned exploration. Working groups were formed in the areas of geology, geophysics, bioscience, geochemistry, astronomy, lunar atmospheric measurements and cartography. In a general sense, the conference looked at five major areas: Apollo, Lunar Orbiter, Apollo Extension System-Manned Lunar Orbiter (AES-MLO), Apollo Extension System-Manned Lunar Surface (AES-MLS) and Post-AES. At the end of the conference, each working group published its report. These reports were compiled into a Summary, published by NASA as SP-88. The section on AES-MLS specifically addressed the requirements for extended manned missions on the Moon. It is worthwhile to quote the enumerated topics from the Summary:

The primary objective of analytical devices used on the lunar surface should be to extend the power of the observer to differentiate materials that have similar characteristics. The optimum sample return capability would be between 200 and 270 kg (450-600 lb) per mission. The following basic types of equipment are required for this phase of lunar exploration:

1. Automatic position recording systems. Essential for tracking and recording the movements of the astronaut and the roving vehicle, and knowing the orientation of the camera. The system would automatically telemeter this information back to Earth or to the LEM.
2. Local Scientific Survey Module (LSSM). This surface roving vehicle should have the capability of carrying either one or two suited astronauts and scientific payload of at least 270 kg (600 lb). An operational range of 8 km (5 miles) radius is a minimum, and 15 km (9 miles) would be more useful. Remote control of the LSSM would also be advantageous both before and after the arrival of the astronauts.
3. Lunar Flying Vehicle (LFV). A LFV would be useful for extending the operational range of the AES and for studying features inaccessible to the LSSM due to topography. It should be able to carry a 135 kg (300 lb) scientific payload over a distance of 15 km (9 miles). Continued study should determine how effectively it can be employed in surface operation.
4. Lunar Drills. The development of a 2.5 cm (1 in) drill capable of penetrating to a depth of 3 m (10 ft) in either rubble or solid rock is recommended. It should be

operable from a roving vehicle. It is necessary for lunar heat flow studies and for obtaining biological samples.

SP-88 was perhaps the first formal NASA document calling for a Lunar Roving Vehicle. In addition, it called for a positioning system relative to the rover, and the need for lunar drills. Three of the four recommendations would eventually be implemented. The Lunar Flying Vehicle continued to be the topic of serious discussion for several years.

A second conference was held at the University of California in Santa Cruz in 1967. This conference also proved pivotal to the direction of future Apollo missions. The primary goal of the conference was to arrive at a scientific consensus on future manned and unmanned exploration programs and the hardware necessary to achieve them within the Apollo Applications Program (AAP). The conference proved to be more contentious than consensus, however. Different working groups advocated different means of lunar surface mobility. In particular, the Geochemistry Working Group advocated a large lunar flying vehicle, while the Geology Working Group supported a combination of small Lunar Flying Units (LFU) in conjunction with the

General Motors' Defense Research Laboratories (GM-DRL) division performed extensive vehicle mobility studies for NASA during the 1960s as well. This MTA built by DRL is shown traversing a boulder obstacle field. (NASA/MSFC)

LSSM. At this conference, the attendees clearly saw the LSSM as a dual-mode vehicle, operating either manned or unmanned. Most interestingly, the position was clearly put forth that the Saturn V should be used in the dual-launch capacity. One Saturn V was viewed as insufficient to get men and material to the Moon as envisioned by the conferees. The summary of the conference had this telling statement: "The dual-mode LSSM is more complicated and has greater capability than the vehicle presently planned." Many of the capabilities of the dual-mode LSSM would, in fact, appear decades later on the Martian rovers *Spirit* and *Opportunity*, such as stereo TV (camera) broadcast capability, dead-reckoning navigation, rock analysis, and other features. The "vehicle presently planned," was a cryptic reference to the Lunar Roving Vehicle that was being more seriously considered in the face of declining NASA budgets, which had peaked in 1965 at 5.25 billion dollars The published summary of the conference (SP-157) admitted to the possibility of the recommendations of the conference not being implemented in the future, and presented a fallback position in which a future conference might be necessary to redefine lunar missions, if the dual Saturn V launch mode could not be implemented due to severe budgetary restrictions.

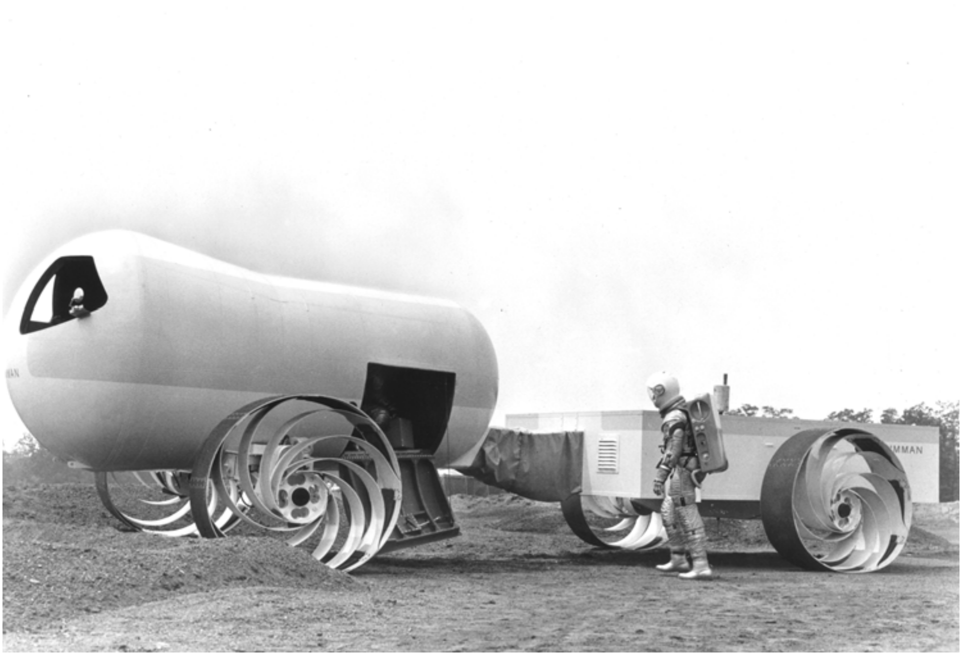
Towards the end of the Santa Cruz conference, chairman Wilmot N. Hess formed the Group for Exploration Planning, made up of key members of the working groups. They would work with NASA's Manned Spacecraft Center (MSC) towards implementation of the recommendations in mission planning, surface experiments and equipment selection, to support the scientific areas of the lunar missions. Maxime A. Faget was a member of this group and was also director of the MSC's Engineering and Development Branch. His word carried considerable clout, and he estimated the cost of engineering and building the long-range pressurized vehicle recommended at the second conference at upwards of a quarter of a billion dollars. It did not appear that the heavy, complex and expensive LSSM could realistically be funded. However, many of the recommendations to come out of the Santa Cruz conference were, in fact, adopted. Among them were the Apollo Lunar Surface Experiments Package (ALSEP) and other surface instrumentation.

THE LUNAR ROVING VEHICLE WINS THE MOBILITY DEBATE

As late as mid-1968, numerous contractors still held the view of using dual Saturn V launches to support extensive Apollo missions and their considerable hardware requirements. For example, in May 1968 GMDRL became AC-Electronics Defense Research Laboratories and published a presentation titled *Roving Vehicles for Apollo Lunar Exploration Program*. The presentation discussed the work the General Motors division had conducted and its relevant experience in the development of lunar surface vehicles, followed by a technical discussion of dual-mode vehicles, operating either manned or unmanned on the lunar surface, that were compatible with single- or dual-launch missions. Of considerable interest was the photo and description of the Lunar Wheel and Drive Experimental Test Program, which showed a wire mesh wheel reinforced with riveted chevrons (shown within a circular

test fixture), very similar to the eventual wheels used on the actual LRV. The paper was followed up in June with *Dual-Mode Roving Vehicles for Apollo Lunar Surface Exploration*, authored by F. Pavlics, J.P. Finelli, B.P. Miller and R.T. Kowalski. This paper specifically addressed a Lunar Rover design weighing between 273 and 909 kg (600 and 2000 lb) and recognized the necessity of a folding vehicle to fit within the triangular envelope available within Quadrant 1 of the Lunar Module. The paper stated: "The forward and aft chassis extensions are folded over the top of the chassis and the crew station folded onto the main chassis structure. The suspension arms, which are attached to the chassis extensions, are deflected until the wheels are parallel to and within the envelope edges. The suspensions are then locked into place with spring pins. The antennas are folded and the TV mast telescoped to fit the envelope constraints." This paper illustrated the stowage envelope and the actual deployment sequence in photographs of a $\frac{1}{6}$-scale model of the Lunar Roving Vehicle deployed from a scale model of the Lunar Module.

The hope of some in the scientific community, and the belief of the aerospace firms involved in studies that the latter Apollo missions would use two Saturn Vs, evaporated in conjunction with the rapidly declining Apollo budget in the later 1960s. Economic reality now dictated that each Apollo mission would use a single Saturn V, and lunar orbit rendezvous would be the mission mode for getting to and from the Moon. This made weight a prime issue. Any Lunar Roving Vehicle would



NASA also issued contracts for pressurized vehicle studies. Such a vehicle with crew provisions would permit lunar exploration missions lasting days or weeks far from the lunar base. This vehicle was built by Grumman. (NASA/MSFC)

have to be as light as possible and the fanciful pressurized vehicles were no longer seriously considered. However, the LRV, as it would become known, was not universally welcomed. Vehicle weight would impact the amount of precious fuel the Lunar Module could carry for landing and – most of all – hovering to give the mission commander time to locate the best possible landing site. Running out of fuel at this point could prove disastrous to the mission and fatal to the astronauts themselves.

In 1967, Grumman Aircraft Engineering Company, the prime contractor for the Lunar Module (LM), initiated studies on modifying the LM to permit longer duration missions of several days on the Moon; the first generation LMs were only capable of landing and staying on the lunar surface for thirty-six hours maximum. These studies proved beneficial when the company was formally requested by NASA's Office of Manned Space Flight early in 1969 to undertake studies to upgrade the LM to permit the longer duration "J" configuration for the latter Apollo missions. This would eventually include increased payload carrying capacity to the lunar surface with the addition of a Lunar Roving Vehicle.

The decision that the Apollo missions would now use a single Saturn V for the lunar missions irked Sam Romano at GM Defense Research Laboratories in Santa Barbara. He had coordinated much of the early lunar vehicle studies in conjunction with Boeing and had some of the brightest men working there involved with such studies, such as Dr. M.G. Bekker and Ferenc Pavlics. With only one Saturn V to be used, the idea of a Lunar Rover was effectively shelved. However, Romano wanted to find a way to make a lunar vehicle happen. Late in 1968, he traveled to Washington with several of his engineers and met with NASA managers involved with the Lunar Module. Romano wanted to know what space was available for a possible Lunar Rover and what the weight limit might be. He was told that the instrument quadrant to the right of the LM ladder might be available, but the upper limit on the vehicle's weight could be no more than 227 kg (500 lb).

"We went back to Santa Barbara," Romano said in an interview with this author, "and for four months, did studies and came up with a configuration that would fit right in that box and would weigh less than 500 pounds. We made a $\frac{1}{6}$ -scale model of the rover and a $\frac{1}{6}$ -scale model of the LM. We then made a movie of the rover folded up in the LM compartment and filmed it deploying. We took the models and the film to Huntsville and showed it to Len Bradford and some of his engineers. Bradford said, 'We have to show this to Dr. von Braun.' So, we went up to the ninth floor of building 4200 at MSFC. I put the rover model down on the corridor floor. It was remotely controlled and we drove it up to Dr. von Braun's office door. One of the NASA guys knocked on the door and then opened it. We drove the rover model into his office, and von Braun was on the phone. He sat up in his chair, hung up the phone and said, 'What have we here?' That gave us an opportunity to tell him what we could do. After about half an hour or so showing the film and telling him how we could do it, he finally slammed his fist on his desk and said, 'We must do this'."

That series of events is corroborated by Ferenc Pavlics, one of Romano's chief engineers. Pavlics had fled the Hungarian Revolution of 1956 and succeeded in coming to the United States. Dr. Bekker felt Pavlics to be a good intuitive engineer,

Smaller vehicles were requested by NASA as a follow-on program to the larger MTAs. This Bendix-built vehicle is being driven by "Putty" Mills and Harrison Schmitt at the USGS Cinder Lake Crater Field in Arizona. (U.S. Geologic Survey)

and in 1959 Pavlics joined GM's Defense Research Laboratories, which at the time were in Detroit, Michigan. He later received his Master's degree in Mechanical Engineering from the University of Michigan. When the division was moved to Santa Barbara, California in 1961, Sam Romano, Dr. Bekker, Ferenc Pavlics and many others moved with it.

"We went to Huntsville and got a very good reception from the technical group of people to our presentation," Pavlics recalled in 2005. "To embellish our presentation, we built a $\frac{1}{6}$ -scale model of the proposed concept and we took that along with us to the presentation. It was a radio remote-controlled model with electric motors, and steering which was functionally an exact representation of our proposed concept. It could be folded up into this triangular envelope which NASA described as available for this purpose. We did demonstrate this during the

Huntsville visit. After the technical presentation, they suggested we show it to Dr. von Braun. This model was actually built by me. My wife even stitched the seats. We used my son's G.I. Joe with an astronaut suit. It was just the right scale. Dr. von Braun was very surprised to see something like that coming into his office. We explained what the concept was all about. It took a considerable amount of selling effort to get the idea across that it was possible to do and it could be done within the timeframe. I still have this model in my possession."

On 7 April 1969, Dr. von Braun announced that he was establishing a Lunar Roving Task Team at MSFC, and selected Saverio "Sonny" Morea to be the program manager. Morea's affiliation with von Braun dated from his guidance and control work on the Redstone ballistic missile. He then worked on the rocket engine of the Jupiter IRBM and then the H-1 engine for the Saturn I. Morea had managed the successful F-1 main engine development and manufacturing program for the Saturn V as well as its J-2 upper stage engine, before being given the equally challenging task of managing the LRV program.

THE LUNAR ROVING VEHICLE REQUEST FOR PROPOSALS

In May 1969, George E. Mueller, Associate Administrator for the Office of Manned Space Flight, selected the Lunar Roving Vehicle as the means Apollo astronauts would use to traverse and explore the Moon. On 26 May, the crew of Apollo 10 – Thomas P. Stafford, John Young and Eugene Cernan – splashed down in the Pacific Ocean after a completely successful mission designed to duplicate every step of Apollo 11, apart from landing on the surface. On 29 May, the Office of Manned Space Flight issued a memo to MSFC, the Manned Spacecraft Center and Kennedy Space Center titled: "*Requirements assessment for Lunar Roving Vehicle (LRV)*".

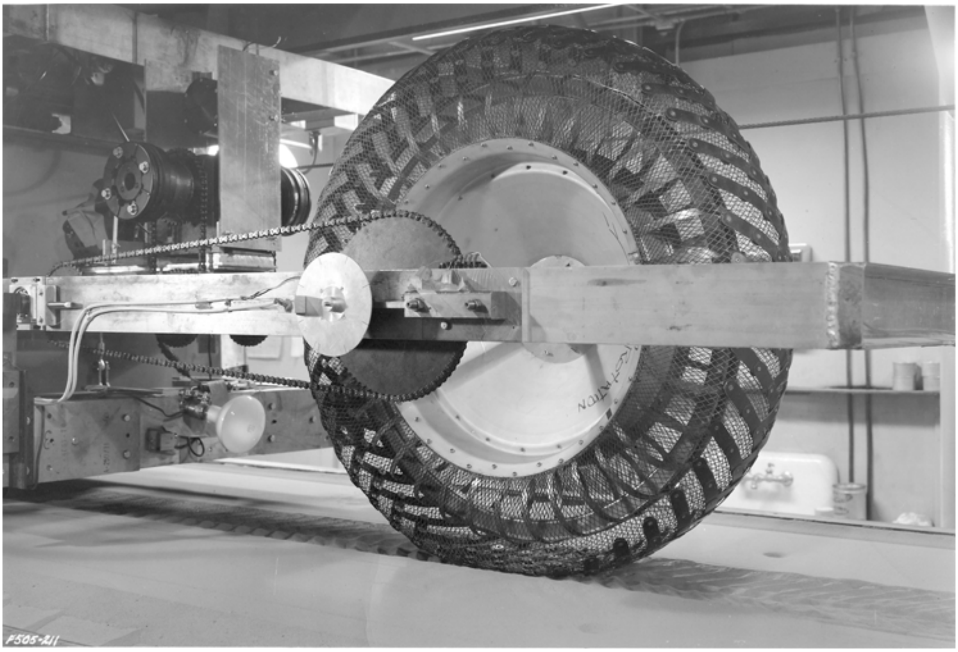
Then, on 11 July 1969, shortly before the successful Moon landing of Apollo 11, the LRV Task Team issued a Request for Proposals (RFP), No. IL-LRV-1, from twenty-nine NASA contractors, based on the extensive previous lunar mobility studies and testing. Within the RFP, the Scope of Work listed twenty-two specific requirements for the vehicle. They were:

1. Configuration – the LRV will be a four-wheel vehicle powered by storage batteries with each wheel powered by an electric motor. The LRV will be operated manually by one astronaut.
2. Weight – 400 lb maximum which includes the tie-down and unloading system.
3. Cargo Carrying Capacity – 100 lb of science experiments plus two astronauts at 370 lb each for 840 lb total or alternate of one astronaut plus 470 lb, and also to provide the capability of carrying 70 lb of lunar soil and rock samples.
4. Range – the LRV will be capable of performing four 30 km traverses in a 78-hour period for a total of 120 km.
5. Life – the LRV will be capable of an operational life on the lunar surface of a minimum of 78 hours during the lunar stay.
6. Stowage – the LRV will be capable of being stowed in one bay of the Extended

LM. The CG and the envelope of the LRV must be consistent with the constraints outlined in the LM interface exhibit of this Statement of Work.

7. Speed – the fully loaded LRV will be capable of a sustained velocity of 16 km/hr on a smooth mare surface. The LRV speed shall be continuously variable from 0-16 km/hr.
8. Deployment – the LRV will be capable of being deployed with minimum activity by one astronaut.
9. Sterilization – not required, but the contractor shall indicate his approach to reduce the level of biological contamination to be consistent with present LM requirements.
10. Obstacle Negotiation – step obstacle 30 cm high with both the wheels in contact at zero velocity; crevasse capability of 70 cm wide for both wheels at zero velocity.
11. Slope negotiation – the fully loaded LRV will be capable of climbing and descending slopes of up to 25 degrees.
12. Single-Point Failures – the LRV system and subsystem design will be such that no single-point failure shall abort the mission and no second failure shall endanger the crew.
13. Operation – the LRV will be capable of being checked out and operated by one astronaut on the lunar surface with the controls and displays located on the vehicle.
14. Crew Safety – the LRV design and the LRV operational procedures shall include the required provisions to ensure crew safety from all identified hazards. (Examples of hazards are solar glare from reflecting LRV surfaces, lunar surface roughness, vehicle instability, etc.).
15. Reverse – the LRV will be capable of backing up with provisions for the driver to have visibility when operating in this mode.
16. Dust – critically-affected surfaces or components shall be designed to minimize degradation by dust and should be located such that dust coverage is difficult.
17. Clearance – the LRV will be capable of a minimum ground clearance of 35 cm on a flat surface.
18. Lateral and Longitudinal Static Stability – minimum pitch and roll angles of 45 degrees with full load.
19. Turn Radius – approximately one vehicle length.
20. Emergency Aids – emergency aids will be considered to help free the vehicle (e.g., hand holds).
21. The power system shall provide a contingency 150 watts over and above the LRV requirements while driving.
22. The contractor shall specify the LRV acceleration capability in the proposal.

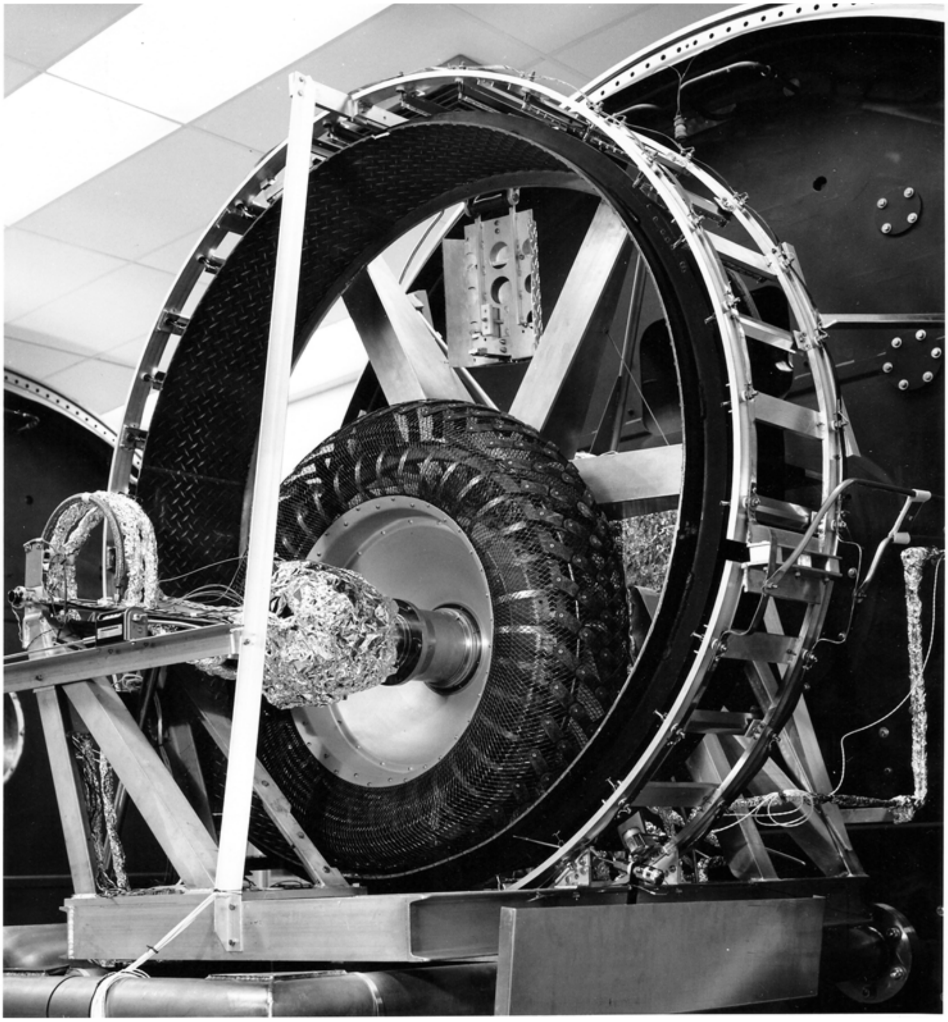
These were not the only requirements given in the Statement of Work. The contractor also had to address the needs of mobility, controls and displays, electrical power supply, scientific equipment, equipment thermal control, caution and warning indication visible to the astronauts, deployment, crew station accommodations, and more.



GM-DRL performed extensive wheel studies in the late 1960s as part of their vehicle concepts for NASA. This is an early wheel design being tested on a sand trench fixture. (NASA/MSFC)

With the euphoria of the successful lunar landing by Neil Armstrong and Edwin Aldrin and the imminent return of the Apollo 11 crew, a bidders' briefing was held on 23 July at NASA's Michoud assembly facility east of New Orleans, Louisiana. Only four companies accepted the challenge of building the LRV and were prepared to deliver proposals. Present were representatives from the Boeing Co., Bendix Corp., Grumman Aerospace and Chrysler Space Division. Some were shocked to learn that they had only six weeks to prepare their proposals for consideration. It was during this time that Morea attended a debriefing of the Apollo 11 crew at Johnson Space Center in Houston, in order to provide additional insight for the prospective bidders for the LRV subsequent to the 23 July briefing.

MSFC evaluated the LRV contractor proposals during September and October. By the end of September, they had eliminated Chrysler and Grumman, leaving Boeing and Bendix. It should be stated here that Bendix had committed itself in 1960 to long-range research and development of lunar exploration vehicles. It had invested over twelve million dollars of its own money in this pursuit. The corporation realized that in order to obtain a return on this investment, it would have to win the LRV contract. During October, MSFC worked on preliminary contract negotiations with Boeing and Bendix. Saverio Morea published the results in an internal document dated 23 October 1969. Boeing's negotiated baseline was \$17,280,000 with a target vehicle weight of 181.6 kg (399.5 lb). Boeing was counting



GM performed durability tests on its wheel and drive motor concepts on a number of different fixtures. (NASA/MSFC)

heavily on its subcontractor, GM's Defense Research Laboratories, to help deliver the LRV at that price and that weight. Bendix's negotiated new baseline was $22,957,000 with a target vehicle weight of 180.9 kg (398.0 lb). Other factors were of prime importance to MSFC, including the depth of the vehicle design and its projected reliability, human factors, manufacturing capability, the experience of the management team, the attitude of the individuals during presentations and negotiations, and their ability to meet performance goals and schedules.

On 28 October, MSFC formally announced Boeing as the winning bidder – at $19.6 million – for the LRV contract. This was a tremendous blow to the Bendix

Corporation. Boeing promised delivery of LRV-1 to the Kennedy Space Center on schedule for April 1971. Now it came time to negotiate the contract itself. The timetable to deliver the LRV was unprecedented; most Apollo man-rated systems took three to four years to complete. But the task facing Boeing was really much bigger, and the actual contract spelled out what they had to accomplish to fulfill its terms. Morea knew from experience that costs, timetables and performance goals could spiral out of control (as they had on some other Apollo systems) and he was determined that would not happen with the Lunar Roving Vehicle.

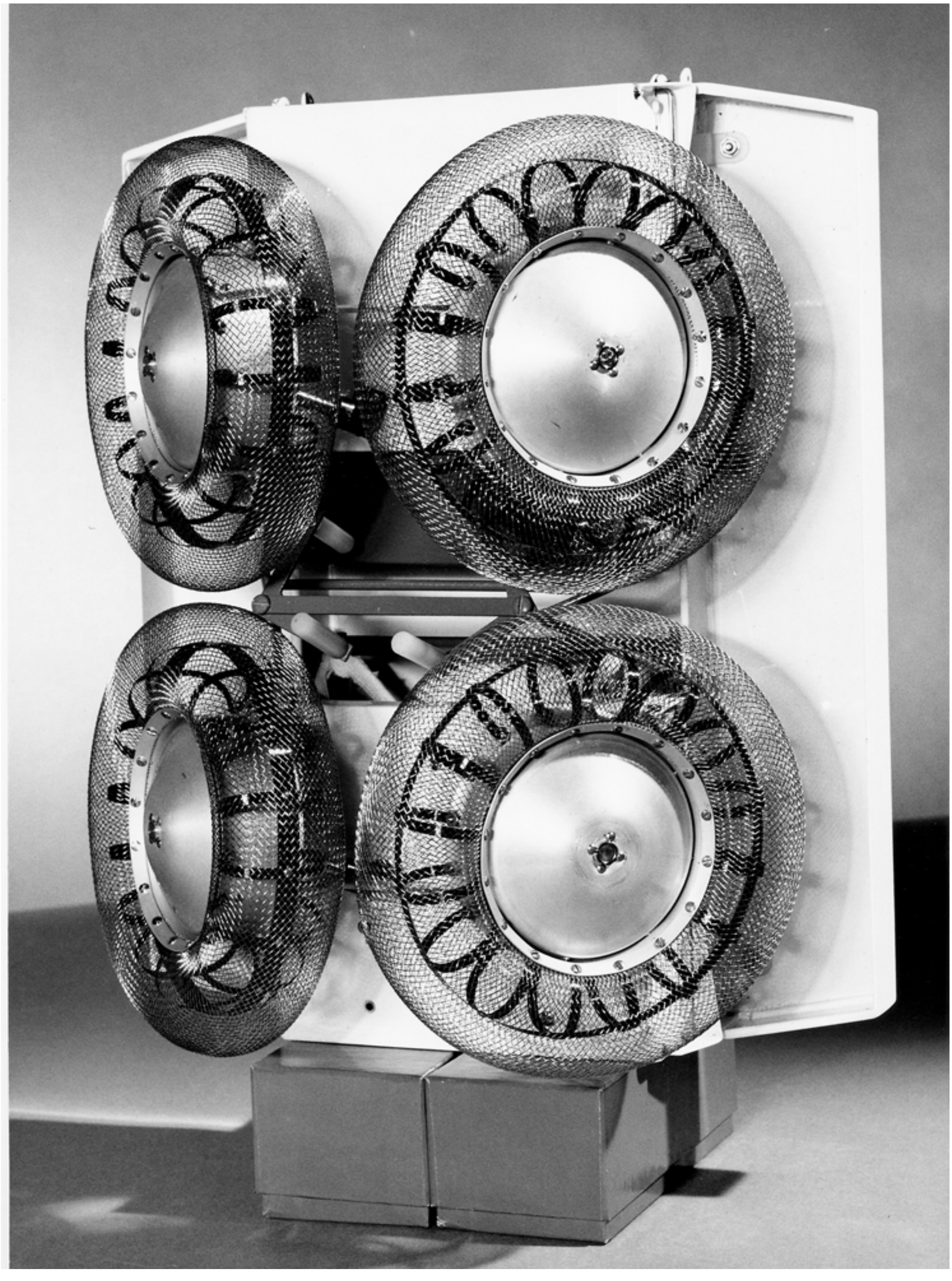
"What stands out in my mind," Morea stated to this author, "was the type of government contract we had with Boeing. We recognized they were the low bidder. How did we protect the government's interest? The contract was written in such a way as to provide Boeing an incentive bonus if the program and vehicles were delivered for the 19.6 million dollars they stated it would cost. However, if the program were grossly over budget, Boeing would receive only a small percentage over and above the 19.6 million to cover additional expenses. In addition, there was a vehicle performance clause that was structured much the same way, which essentially stated that if the LRVs failed to perform on the Moon, Boeing would receive only one per cent of the contract amount above costs. The third variable was the schedule. NASA was ready to put forty million dollars into this project, and we didn't want them to spend all that money and then not deliver the hardware in sufficient time to fly on Apollo 15, 16 and 17. So we put another incentive in that said if they didn't deliver the LRV in time for Apollo 15, they would not collect their entire contract fee."

Based on his considerable experience on the F-1 engine program and how changes in design affect not only schedule but cost, Morea was adamant about limiting changes to the LRV during the engineering phase. To accomplish this, Marshall Space Flight Center laid down very specific performance goals the LRV had to meet based on known lunar surface features.

"We said to Boeing," Morea vividly recalled, "'Look, this thing has got to work on the Moon and this is what we know about what it's got to do: It has got to be able to go in and out of craters that are two feet deep and two feet wide. It's got to be able to go over a rock that's one foot high. It's got to be able to travel at a certain speed. It's got to be able to climb a hill of 25-degree slope and it's got to be stable in roll and pitch on a slope of 45 degrees.' Anything necessary to meet these requirements, Boeing had to do within the cost of the program."

THE BOEING-MARSHALL SPACE FLIGHT CENTER COLLABORATION

The Marshall Space Flight Center had always been a very autonomous NASA center, whether it was engineering and building its own hardware in support of the Apollo program, or overseeing contractors responsible for building the hardware MSFC required. Although Boeing won the contract to build the LRV, test units and related equipment, MSFC would remain very much in Boeing's back pocket for the entire duration of the program. Marshall managers and engineers knew from



GM-DRL built a $\frac{1}{6}$-scale model of a proposed LRV design in 1968 to illustrate the stowage and deployment from the Lunar Module. GM worked closely with Boeing in preparation of the LRV proposal to NASA. (NASA/MSFC)

experience that very close collaboration between the contractor and the NASA engineers was essential to ensure that any problems arising would be addressed and resolved in a timely manner to stay on schedule and on budget. This collaboration was also to ensure that the contractor did not stray too far afield in its design engineering, adding undue complexity or unwanted additional cost and impacting on the delivery deadline. While this was certainly true of practically every piece of Apollo hardware, it was especially true for the Lunar Roving Vehicle because of the compressed development and production schedule.

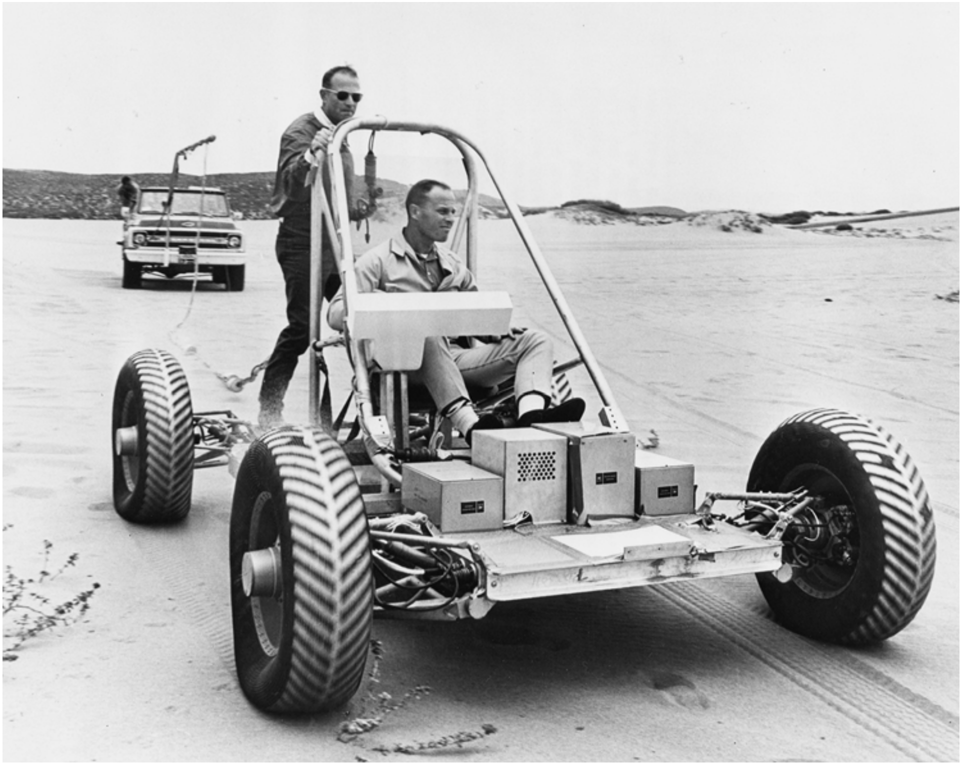
What was MSFC's structure to handle the LRV program with Boeing? Morea headed up the LRV Project Office, but there were no individual departments within that office to handle the various systems that would comprise the LRV. Instead, the Marshall Center relied on its various laboratories, divisions and branches to work on design development with Boeing and its subcontractors. It was a system that had worked well for the development of the Saturn launch vehicles.

"There was no one specific area at Marshall for development of the LRV," Morea stated. "There were areas in each of the Laboratories that had a responsibility for a particular system. We had an Avionics Laboratory to develop navigation, Structures and Propulsion handled those areas, Human Factors handled those issues, and so on."

The MSFC also had to coordinate with other NASA centers in areas where the LRV would impact upon spacecraft design or crew training. There were issues involved with the Lunar Module that would carry the LRV. The LM came under the purview of NASA's Manned Spacecraft Center in Houston, Texas, and they were quite firm in stating that they would not allow any radical changes to the LM to accommodate the LRV. The MSC also imposed weight limits for the vehicle. MSFC also had to coordinate with the Kennedy Space Center (KSC), which involved everything from LRV checkout and flight validation, to deployment tests and crew training, both in the air and on the ground at KSC itself. The LRV program would even involve other governmental entities, such as the U.S. Geologic Survey and the Army Corps of Engineers. The LRV may have been small in relation to such gargantuan vehicles as the Saturn V and its crawler transporter, but it would prove just as all-encompassing in its design development, construction, testing, flight readiness and crew accommodation and safety.

THE LRV: A SPACECRAFT WITHOUT PRECEDENT

The Apollo Command Module built upon the lessons learned from the Mercury and Gemini capsules. The Saturn V drew heavily from all that was learned from the Saturn I and other smaller launch vehicles. The Lunar Roving Vehicle, however, had no such evolutionary legacy. It was a spacecraft unlike anything else ever done by the United States space program. Boeing's LRV project manager in Huntsville, Henry Kudish, wrote in the July 1970 issue of *Space Flight* that the LRV was, in fact, "a very complex spacecraft." However, MSFC and the Boeing-GM team did have nearly a decade of previous vehicle studies and prototypes to draw upon that



GM-DRL was responsible for the Mobility and Electrical Power Subsystems of the LRV. The company built this test mule to validate early hardware designs. This vehicle received its electrical power via a cable from the truck following behind. Astronaut Jack Lousma drives, with astronaut Gerald Carr (standing). Both men would later fly on Skylab missions. (Courtesy: NASA/MSFC)

dramatically focused the various systems that would ultimately make up the final Lunar Roving Vehicle design. That work certainly contributed not only to successfully meeting the mission requirements and deadlines, but also to the utter reliability of the LRV while operating on the Moon.

Boeing's contract called for the company to build four flight-ready LRVs. In addition, it was required to provide a full-scale mockup to make sure the vehicle met the astronauts' human factors requirements; a mobility test unit to assist in developing and verifying the design of the electric motors, wheels, suspension, hand controller and drive control electronics; a Lunar Module unit to determine the stress loads on the Lunar Module and check for envelope clearances; and two one-sixth-weight units to test the deployment mechanism that would unfold and deploy the LRV from the Lunar Module. On top of these, they had to supply a 1-G unit for use by the astronauts for training in either shirtsleeve casual dress or full-up EVA suits; a vibration test unit to ensure both the LRV and the LM would withstand the stresses

that accompanied the launch, space flight and landing on the Moon; and finally the qualification test unit, which was essentially a complete LRV but would be used for testing in vacuum and extremes of temperature.

Like many other flight hardware development programs within project Apollo, the Lunar Roving Vehicle was a prime example of concurrent engineering; the demanding schedule would allow nothing else. At first glance, the proposed LRV appeared relatively straightforward since very little of the vehicle was actually hidden, but in fact it was deceptively complex, being made up of eight primary subsystems. These included the Mobility Subsystem, the Electrical Power Subsystem, the Navigation Subsystem, the Communications Subsystem, the Thermal Control Subsystem, the Crew Station Subsystem, the Control and Display Subsystem, and the Deployment System.

While not all of these subsystems needed backup capability, the mission-critical systems did require redundancy. "That included the ability to steer the vehicle," Morea emphasized. "One of the nightmare scenarios was, 'What if we get to the Moon and something happens to the electronic steering and we don't have the capability of steering the vehicle?' It would be a total loss for us. So, we had redundant steering so that both the front and rear wheels could steer. All four wheels were electrically driven so even in the unlikely event of losing three of the drive motors, the remaining motor had enough torque to get the LRV slowly back to the LM."

Boeing had only ten weeks to nail down the engineering details of the eight systems before it would have to present the entire vehicle design during a preliminary design review. That design review took place on 28 and 29 January 1970 at MSFC, involving roughly 120 personnel from the Center in Huntsville, as well as Boeing engineers and managers and those from Boeing's primary subcontractor, General Motors, plus others involved directly or indirectly with the LRV program. Astronauts John Young, Charles Duke (both of whom would fly on Apollo 16) and Gerald Carr were also present to review the design and offer their essential input. The purpose of the preliminary design review was to ensure that the design presented met the Statement of Work and contract details, but was realistic both in its design and schedule delivery. Two of the systems Boeing presented came under criticism as overly complex: the navigation system and the deployment system. Every aspect of the LRV Boeing presented was discussed and out of that design review, work immediately began on the design engineering of these systems. The Critical Design Review would follow in June 1970 to give approval for production of the LRV. As it would turn out, the next year would prove as rugged and unpredictable as the lunar surface itself.

THE YEAR OF DISCONTENT: 1970

One of the key contract provisions between Boeing and MSFC was the selection of the A.C. Electronics Defense Research Laboratories to be the subcontractor for the largest system making up the LRV, the Mobility Subsystem. This consisted of the

wheel assembly, suspension assembly, traction-drive assembly, steering assembly, drive control electronics, brakes and hand controller assembly. The folding chassis itself, which was also part of the mobility subsystem, would be engineered and built by Boeing. But it became clear by mid-January 1970 that Boeing would have problems with its subcontractor in endeavoring to meet cost, weight and schedule milestones. Only three months had passed since contract signing, and already the LRV program was over budget, there were fears of schedule slippage, and the LRV was over its 181.8 kg (400 lb) target weight. Program management logistics were showing the difficulty of coordinating the work between Boeing, its subcontractor, the NASA centers and the numerous MSFC departments working on the LRV's subsystems. After nearly a decade of Apollo program management, MSFC knew how to manage large programs, but the LRV was beginning to slip away from its control in several areas.

There was a program review at the end of February, and on 2 March, Saverio Morea sent a letter to Henry Kudish, Boeing's LRV program manager in Huntsville, detailing the reasons for schedule slippage and cost overrun, and requesting the company's detailed LRV plans, a schedule assessment, and a recovery plan. Morea was clearly dissatisfied with Boeing's performance to date, and he expressed the fear that Boeing would miss delivery of the first flight unit by one to three months, thereby delaying the launch date. Kudish met with Morea on 5 March to address the crucial issues and in a letter the following day, stated that the company's recovery plan would be submitted by 10 March. MSFC continued to put pressure on Boeing to accelerate its design development and to better control its subcontractor. In addition, Morea established a MSFC "Tiger team" to assess all technical, schedule, cost and programmatic aspects of the LRV program at Boeing and General Motors. One of the issues the Tiger team uncovered was the lack of a definitive contract between Boeing and General Motors' AC-Electronics Defense Research Laboratories.

During a static load test of the chassis at Boeing on 29 April 1970, structural failure occurred before the required test load had been reached. At the time this seemed no less significant than the fuel tank failures that occurred during development tests of the Saturn V launch vehicle years before. Nevertheless, Boeing, GM, MSFC and the many companies working on the LRV program labored to resolve the engineering and schedule problems during May. With the Critical Design Review looming in June, there were serious questions regarding Boeing's ability to meet the letter of the contract. On 18 June, Morea hosted a confidential meeting in Huntsville to discuss government options on whether to continue or terminate the LRV program. Present were several individuals involved in the area of NASA contracts and one from the Chief Counsel's Office. They discussed the pros and cons of either continuing the program or terminating it. One issue sensitive to MSFC was the extremely challenging schedule – roughly seventeen months to deliver the first flight-ready LRV. It was believed that Boeing might use the argument of "impossibility of specification compliance" which might prove detrimental to NASA's case. Also discussed was the fact that the LRV was very much a high-profile program and would be counted on to provide many touted potential discoveries. If

MSFC program manager of the LRV, Saverio "Sonny" Morea, checks an early mockup. The pistol grip hand controller was retained until late in the LRV development program. (Courtesy: NASA/MSFC)

NASA cancelled the program, it would prove damaging to the agency, so it appeared that this was not a viable option. Weighing all the possibilities, it was decided to continue the contract, with its multiple overriding incentives on cost, technical performance, and schedule. Failure by Boeing to meet any of these incentive areas would result in a fee to them of only one per cent.

In the book, *50 Years of Rockets & Spacecraft in the Rocket City* (Turner Publishing Company), Morea explained at length the problems that the program faced:

> "It was during this time that our team experienced some of the most stressful and difficult days. Congress had picked up on the potentially large percentage overrun of a NASA project, and initiated action for the GAO to run a full audit of the program. I was asked to put together a briefing to NASA headquarters personnel.
>
> "Some members of NASA headquarters were critical of the use of a 'performance specification' approach, indicating that it would have been more 'politically' acceptable to have a 100 per cent 'cost growth' rather than a 100 per cent 'cost overrun.' The former puts the blame on the government for directed changes and allows the contractor to earn more profit, while the latter

approach punishes the contractor for perhaps coming in with an undoable low bid just to win the contract, or for mismanaging the project, or both.

"Much to my surprise, I learned that the congressional staffers were so impressed with the incentive contract negotiated and the performance-spec approach used by the MSFC team that they arranged to call off the GAO audit. To our knowledge, never before had a GAO audit ever been called off, once such a request had been made. Ben Milwitski indicated that the congressional staffers were well pleased with how the government's interests were protected and expressed surprise that a contractor such as Boeing would sign such a contract. Needless to say the LRV team at MSFC felt vindicated in their judgments."

One of the cost drivers of the LRV program was the fact that there were more than 600 people working on it. With the bulk of design engineering completed and following the CDR, these numbers were drastically cut to less than 300 by September. The issue of deliverable hardware from Boeing and its subcontractor dogged the program during the summer, but Boeing could finally report that the various LRV units, apart from the flight units needed early the following year, had

Morea studies a Mobility Subsystem test fixture at GM-DRL in Santa Barbara, California during October 1970. (Courtesy: Sam Romano)

all been manufactured by the September-October time frame. Boeing and A.C. Electronics Defense Research Laboratories actually underwent program management changes over a period of months in an effort to accelerate individual component and system qualification testing and manufacturing, and to support delivery of the important 1-G trainer. The decision was made to move LRV manufacturing and testing from Huntsville to Boeing's facility in Kent, Washington, a decision enthusiastically supported by Boeing itself. This also put assembly activity closer to its subcontractor. Due to the cancellation of missions after Apollo 17, the third LRV mission, parts for the fourth LRV were not assembled but were earmarked for spares.

The biggest change Boeing and GM had to confront at this time involved the hand controller. Several astronauts complained about lower arm and hand fatigue and an inability to set the parking brake. A technical review in August at the renamed Delco Electronics Division in Santa Barbara resulted in the Manned Spacecraft Center accepting responsibility to evaluate the hand controller problems and recommend design changes. With input from the astronauts, the MSC proposed changes in the design of the hand controller the following month. These included a T-bar design so that the astronaut's hand rested on top of the grip horizontally, a mechanical reverse inhibit switch included in the grip, an automatic spring-loaded lock on the parking brake and modifications to the brake lock to enable a hard left steering command to release the brake. MSFC directed Boeing to incorporate these changes on 16 September, but there were other concerns. The flex splines in the wheel harmonic drives showed fatigue cracking and subsequent failure during qualification testing and the harmonic drives themselves exhibited low efficiencies in terms of torque. Stress analysis was performed on the failed flex splines and the machining vendor was informed to make proper changes. The harmonic drive qualification units were returned to the vendor for test and evaluation in October.

In mid-October, Dr. Robert Gilruth, Director of the Manned Spacecraft Center, and Dr. Eberhard Rees, the new Director of the MSFC (Wernher von Braun had moved to NASA Headquarters in Washington), along with Saverio Morea and O. M. Hirsh of the Contracts Office, visited Boeing's facility in Seattle and GM's facilities in Santa Barbara. This high-profile trip by MSFC and JSC management served to reinforce to Boeing's management the importance of the LRV Project meeting its technical, schedule, and latest budget objectives for NASA's last three Apollo missions – Apollo 15, 16 and 17

As late as November, deployment system tests revealed problems. The MSC and MSFC did a wholesale review of the system, which called for a complete redesign. The deployment system, like virtually everything else about the LRV, had to be fail-safe. If the LRV failed to deploy correctly on the Moon, the entire mission profile would effectively be lost. Astronaut input on this system was vital as well. Charlie Duke contributed considerable design information to assist Boeing in the redesign and a drawing review of the new design was scheduled for the end of November. This was also the month that Boeing finally received the change order for the new hand controller and implementation of the design change was made with stunning speed, since qualification hardware of the new hand controller was needed by December.

The schedule for completing the No. 1 flight unit for Apollo 15 was accelerated and in fact, the schedule for all aspects of the LRV program was so closely followed by MSC and MSFC, as well as Boeing and its subcontractors, that the Qualification Test Unit was scheduled for delivery from A.C. Delco to Boeing on 14 December 1970 at 3:26 a.m. The QTU would undergo an exhaustive series of acceptance tests at Boeing during January, February and March to find any potential failures. Any necessary changes would be implemented and incorporated in the flight units. Nevertheless, in his notes reviewing the LRV program that December, LRV/Apollo Program Director H. J. McClellan could confidently write: "Consolidation of manufacturing and engineering liaison activities at Kent, Washington, adjacent to the test activity, has significantly improved our confidence to meet the 1 April 1971 commitment for delivery of the No. 1 flight article."

Boeing completed assembly of the first flight unit, LRV No. 1, and began the series of acceptance tests on the heels of the Qualification Test Unit. The first flight unit passed all the acceptance tests and Morea received the call from Boeing informing him LRV No. 1 was ready. Morea flew to Seattle and on 10 March 1971, accepted the first LRV destined for Apollo 15. It was folded, secured in its shipping fixture and prepared for its flight to Kennedy Space Center two weeks ahead of schedule.

The Lunar Roving Vehicle subsystems

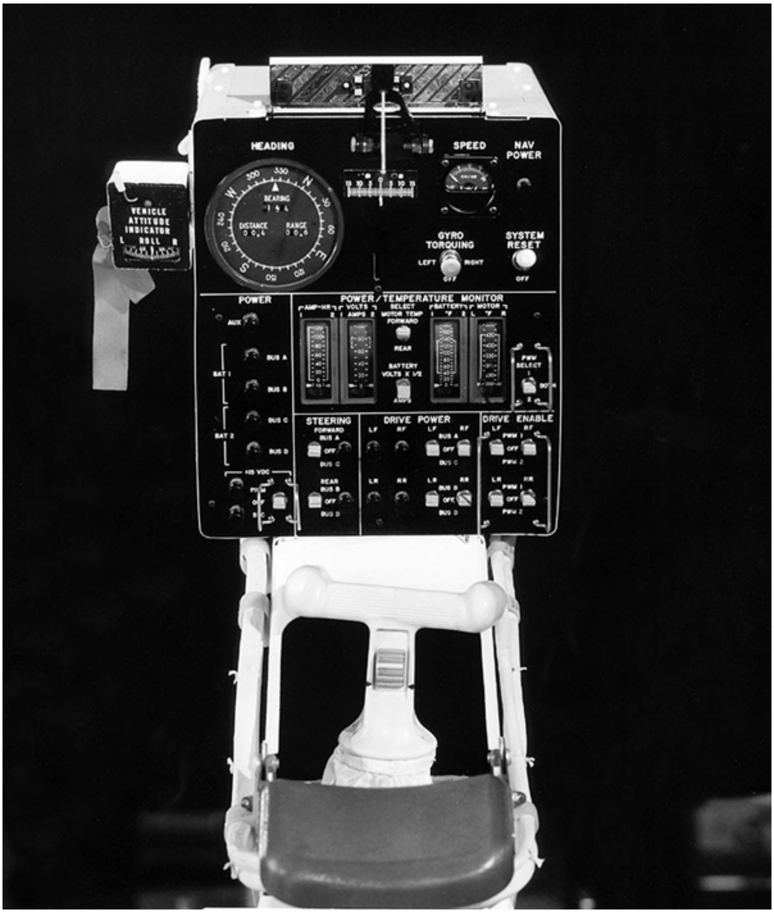
The Lunar Roving Vehicle had eight primary subsystems. These subsystems were engineered and tested concurrently. It is extraordinary that the design, testing, production and delivery of the flight units was achieved in less than eighteen months.

THE MOBILITY SUBSYSTEM

The largest subsystem of the LRV was the Mobility Subsystem, which consisted of the chassis, and the equipment and controls required to suspend, propel, brake and steer the rover. This included the forward, center and rear chassis, suspension, wheels, drive control electronics, traction drives, brakes, steering linkage, fluid dampers (shock absorbers) and the hand controller used to steer, accelerate and brake the LRV. Boeing brought in General Motors and its A.C. Electronics Defense Research Laboratories (later called Delco Electronics Division) as a subcontractor to engineer these critical systems. To get the compact envelope necessary to fit into the Lunar Module's quadrant to the right of the ladder, the rover would have a front and rear folding chassis, with attached suspensions folding inward on top of the center chassis section. In addition, the suspension system had to be designed to fold 135 degrees toward the centerline of the chassis during the folding of the front and rear sections. Aluminum alloy 2024 and 2219 was used extensively throughout the mobility subsystem.

The LRV's chassis, suspension and traction drives

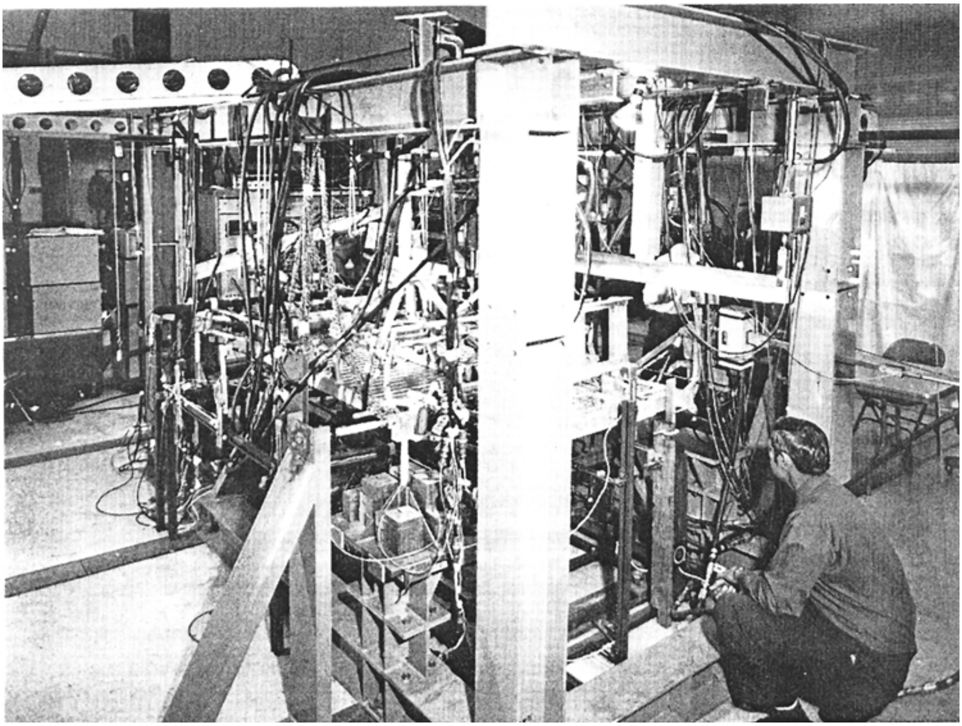
"I was the engineering manager of the group which came up with the folding concept and eventually the vehicle part of the Lunar Rover," Ferenc Pavlics stated in an interview with this author. "The vehicle was over 120 inches long, but the space available was only about sixty inches, so it really had to be folded so that it took up half its length. In addition, it had to fit into a triangular-shaped envelope, which was one quarter of the Lunar Module descent stage. To accomplish that, I came up with the idea of folding the chassis' ends 180 degrees over onto itself. Then the suspension linkage was designed such that when we folded the wheels under the chassis, they



The final flight-approved configuration of the Control and Display Console featured a non-glare black panel with white instrument and switch nomenclature. The Alarm Indicator flag on top of the console (shown in the Warning position) would flip up when high-temperature conditions existed for the batteries, the drive motors or gearboxes. Note the wire guards around the select switches to prevent accidental position change, and the reverse inhibit switch on the hand controller. (NASA)

took up a 45-degree angle. So, when you folded the suspension links under, and then you folded the chassis extensions on both ends, then it would take up this triangular shaped envelope in the LM quadrant with the belly of the vehicle facing out, while at the same time protecting the critical vehicle components such as the drive motors and steering mechanisms.''

The forward chassis contained the batteries, drive control and navigation electronics. It also contained mechanical provisions for mounting the Lunar Communications Relay Unit (LCRU), the Ground-Commanded Television Assembly (GCTA) on the right and the S-Band High-Gain Antenna on the left.

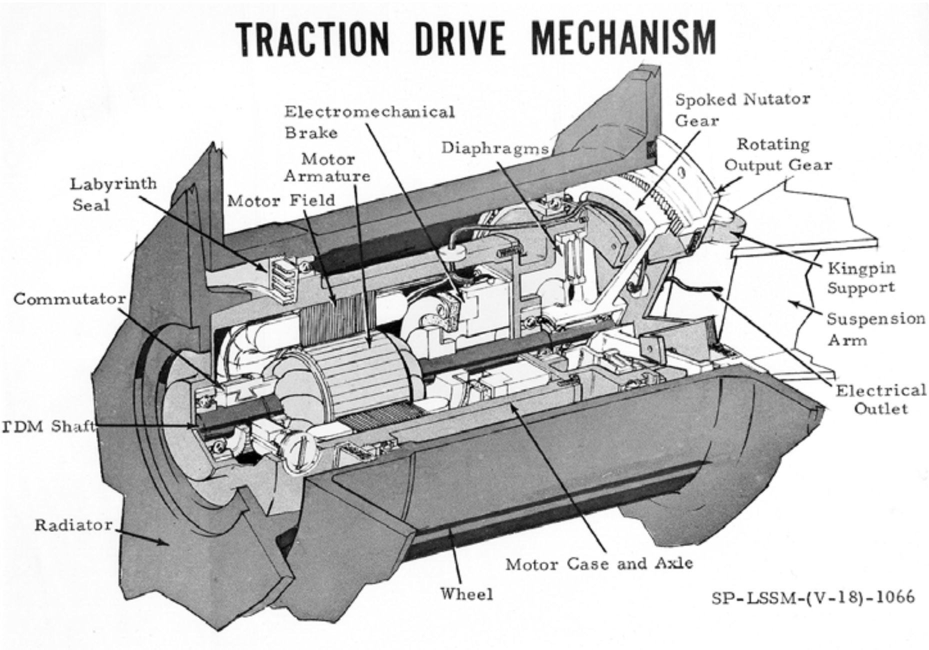


The chassis of the LRV underwent load testing in this test fixture at Boeing. A failure during one test resulted in changes to the LRV's chassis construction. (Boeing)

Hinges with torsion springs were used to unfold the forward chassis during deployment. The center chassis contained the Crew Station Subsystem and the Control and Display Subsystem (explained below). The aft chassis was designed to contain crew equipment stowage and lunar sample collection and storage, which included the LRV Aft Pallet Assembly and Lunar Hand Tool Carrier. Hinges with torsion bars were used to unfold the aft chassis during deployment.

The suspension system was made up of upper and lower triangulated control arms, with the widest portion attached to the chassis by upper and lower steel torsion bars and dampers, and the other end attached to the wheel's traction drive suspension attachment fittings. The torsion bars and fluid dampers (as well as the wire mesh wheels) acted as the shock absorbers. The suspension would prove as challenging to engineer as the traction drive was for Romano's team in Santa Barbara.

"We had problems welding up the suspension system," Romano said. "We would weld them up and test them in a pull fixture. We had a devil of a time making all the weld joints equally strong. We went to North American Rockwell and used their Tungsten Inert Gas (TIG) welding machine. If we didn't get those welds to pull right to get the strength we needed, the thing would not have been man-qualified and we wouldn't have made it. We were sweating those days, I'll tell you."



Each of the four traction drive motors had a rated output of 0.25 horsepower, with a combined output of one horsepower for the LRV. The drives were completely sealed to prevent damage from lunar dust. (NASA/MSFC)

Each traction drive assembly was quite sophisticated and, as history would prove, worked perfectly on the Moon. Each was made up of a ¼-horsepower 36 VDC series-wound brush-type motor that transmitted power to a harmonic drive with a harmonic wave generator operating through an 80:1 gear reduction flex spline.

"The drive train in the wheel was a very unique system," Romano recalled. "The idea came from an Italian engineer, Walter Musser, and he licensed it to United Shoe Machinery in Massachusetts which built them for us. That was a headache, let me tell you. During testing, after several thousand revolutions, the flex spline would fatigue and crack. We worked with United Shoe Machinery and our metallurgists to come up with various methods of annealing the steel spline. The reason we had the flex spline was so the rotating parts could be sealed and would not be subjected to the vacuum of space and the potential intrusion of lunar dust. In a vacuum, if the bearing was lubricated, the lubrication would boil off. Also the DC motor, which had a carbon brush, required moisture in order to survive when it was running on the commutator. So the motors were pressurized with nitrogen, having seven per cent moisture so the brushes wouldn't wear out. [Author note: Additionally, a special fluorinated hydrocarbon lubricant called "Krytox" was used as an internal lubricant in the harmonic drive.] I went back and forth several times to try to get them to toe the line, but they came through and delivered spacecraft-quality units."

During development of the traction drive, a program was also underway to

develop brushless motors for use on the LRV, but in the end Saverio Morea felt more confident in the proven brush-type motor design. Speed control of the motors was the job of Bruce Velasco and was achieved using pulse-width modulation from the movement of the hand controller. Within each traction drive was a magnetic reed switch that activated nine times during each wheel's revolution to determine speed, odometer and navigation readings. The traction drive was fitted with a mechanical brake that was activated via a cable connected to a linkage in the hand controller. Moving the hand controller rearward cut power to the drive and simultaneously activated the mechanical brake. In addition, the traction drive incorporated a free-wheeling bearing; in the event of a drive failure, the drive could be decoupled and allowed to free-wheel using this bearing. Tests determined that the rover would be able to operate – that is, get the astronauts back to the LM – with only one traction drive operating and the other three decoupled. To this business end of the traction drive was attached the most visually distinctive component of the Lunar Roving Vehicle – the wire mesh wheel.

A wheel like no other

The design of the Lunar Roving Vehicle's wheels reflected the years of previous development that had taken place at GM's Defense Research Laboratories in Santa Barbara, initially for the JPL/NASA Surveyor Lunar Roving Vehicle Program (SLRV) in 1964 and 1965, and then under the 1966-1967 MSFC Wheel and Drive Program contract. GM also did extensive soil bin testing of many types of metal wheels during these programs, as well as many studies and development tests performed in relation to lunar surface mobility, before settling on the patented wire mesh design. When the RFP for the Lunar Roving Vehicle was issued to contractors for bids, a lot of preliminary work had to be performed with regard to the lunar terrain and lunar soil itself. About a year-and-a-half before the start of the LRV program, a Lunar Surface Engineering Properties/Trafficability Panel was formed at Marshall Space Flight Center in Huntsville. The panel was co-chaired by Dr. Nicholas Costes at MSFC and Mr. Otha H. Vaughn. In 1956, Vaughn had come to Huntsville with von Braun's U.S. Army Ballistic Missile Agency team. By the late 1960s, he was working in the Aero-Astronautics Laboratory at MSFC when he was asked to join the panel to define a lunar surface and mobility model.

"We tried to use as much information as we could find," Vaughn stated, "such as radar data, thermal data, photometric function data and surface roughness data, to determine how rough the lunar surface was in terms of mobility. I spent many hours looking at photographs from Surveyor and Lunar Orbiter to come up with what I thought was a good representative lunar scale roughness model. Dr. von Braun would come down and look at a lot of the lunar photographs we had. The Lunar Orbiter photos had one-meter resolution and you could actually see where boulders had come rolling down the hillsides. We went back to look at the work by the U.S. Army Waterways Experimental Station which had done a lot of work on off-road vehicle mobility. That was our starting point. I also worked with the U.S. Geologic Survey Astrogeology Branch in Flagstaff, Arizona to come up with good surface model parameters. From a mobility standpoint, we tried to establish the minimum

The wire mesh used in the LRV's wheels was hand-woven using this special loom. During manufacturing, it was formed in such a way that there was no seam anywhere along its compound curved surface. (NASA/MSFC)

amount of ground clearance we had to have for the rover, how wide it should be to get between and around the craters, and what the bearing pressure of the wheel on the lunar soil should be. Dr. Costes and Dr. W.D. Carrier out at Johnson Space Center came up with a good soil model for the lunar surface. Nicholas and I worked together to try to come up with a composite model of the lunar soil, craters and debris.''

The Lunar Surface Engineering Properties/Trafficability Panel was really just the tip of the iceberg with respect to lunar surface studies and tests. A veritable brains trust was brought to bear on various aspects of the LRV with respect to lunar soil, geology and vehicle mobility. The MSFC Astrionics Laboratory provided test data on the operational characteristics of the LRV traction drive system and on implementing the computer program relating to the LRV's mobility performance and power profile analysis mathematical model. The MSFC Space Sciences Laboratory developed the computer program relating to wheel-lunar soil interaction. Lunar soil simulation studies were conducted at the Geotechnical Research Laboratory of the MSFC Space Sciences Laboratory and at the University of California. The soil mechanics experiments from Surveyor were closely studied, and the soil and rock samples from Apollo 11, 12 and 14 proved invaluable. The U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi performed extensive tests with six versions of the GM-Boeing wire mesh wheel using lunar soil simulants of crushed basalt that were similar to samples collected from Apollo 11 and 12, as specified by Marshall Space Flight Center. They also conducted wheeled mobility tests.

These tests were performed under 1-G conditions, but test results were needed at $\frac{1}{6}$ -G to study not only the behavior of the wheel and suspension geometry, but also wheel interaction with the lunar soil simulant.

In the spring of 1970, an LRV Dust Profile Test Program was begun. These tests were conducted by the Simulation Branch in the Mechanical and Crew Systems Integration Division of the Astronautics Laboratory at MSFC. A test fixture was engineered that would replicate, as much as possible, the conditions that the LRV's wheel and suspension system would encounter on the Moon. The fixture included an electrically-powered, 2.5 m diameter bed with a lunar soil simulant trough that could hold ten inches of soil simulant. A single wheel and suspension assembly with fender was mounted to the fixture's vertical shaft. Over this was a 2.5 m diameter by 1.25 m high hemisphere with an air-tight access door to create a vacuum chamber. Instrumentation, lighting and a film camera were mounted inside and there were three viewing ports on this hemisphere. A vacuum pump evacuated the air from the chamber. There were four primary test objectives: (1) to evaluate the performance of the LRV fender designs and configurations, (2) to develop an understanding of the suspended solids behavior of lunar soil with respect to astronaut-vehicle performance and efficiency, (3) to identify and evaluate the problems generated by wheel-fender interaction, and (4) to develop a better understanding of lunar soil mechanics. The tests also proved that the fenders could not be removed to save weight; they were crucial to dust control.

The tests were conducted in two phases. Phase I would take place on the ground

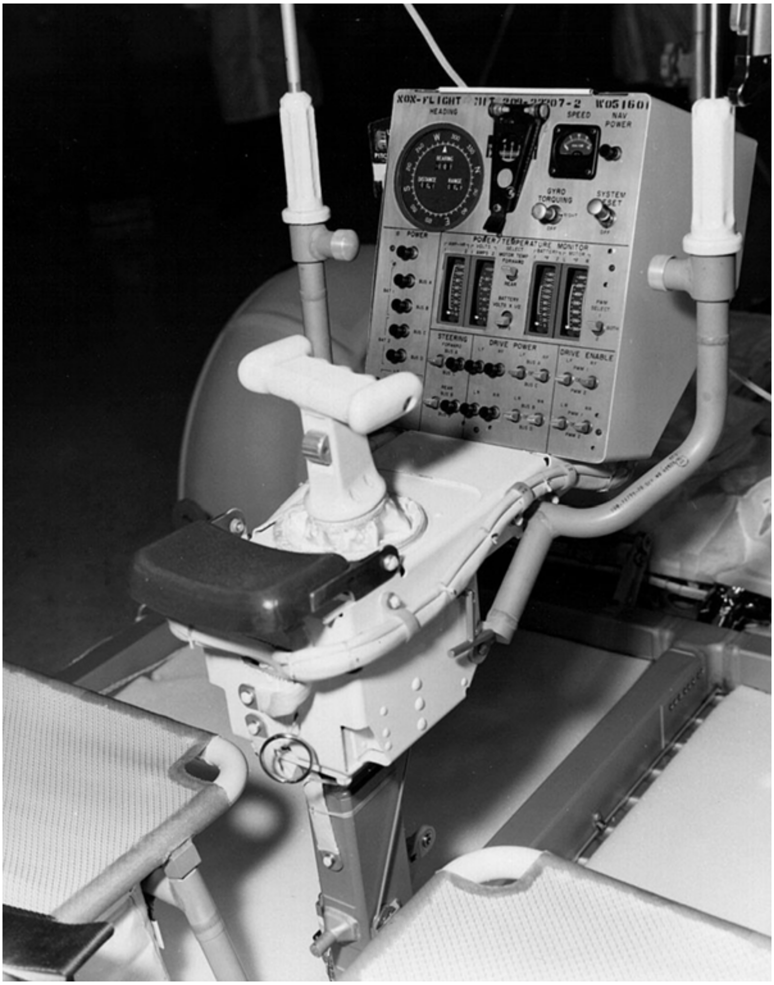
The finished wheel assembly of the LRV weighed a mere 5.4 kilograms. Despite the often rugged lunar surface conditions during Apollo 15, 16 and 17, the LRV did not experience a single wheel failure. (NASA/MSFC)

to establish the proper function of the test fixture and to learn from preliminary test results. This phase was instrumental to the effective design of the fender; to contain and control the path of lunar soil simulant to prevent it from being disbursed over the rover or the astronauts. These tests revealed the need for fender flaps and extensions, which were employed to prevent soil from being thrown onto the LRV or astronauts. Phase II involved tests to be performed at $\frac{1}{6}$ -G aboard an Air Force KC-135-A aircraft, which the test fixture was designed to fit inside. These flights were conducted by the Astronaut Office and the Flight Crew Support Division of the Manned Spacecraft Center. The crew would fly parabolic flight profiles that would achieve $\frac{1}{6}$ Earth's gravity. During May 1971, sixty-five tests were performed under these conditions. The four key objectives of the test program were achieved to help validate the wheel and fender design, the interaction of the wheel with the lunar soil stimulant, and the effectiveness of the wire mesh wheel and its riveted chevron tread pattern.

The wheel design effectively evolved from NASA's Lunar Wheel and Drive Experimental Test Program during the MOLAB and LSSM programs. These tests were performed under ambient and thermal-vacuum conditions and two designs were initially evaluated. The first was a metal-elastic wheel with a flat metal tread and a complex of interior circular cross-section metal springs. The second design was a wire frame wheel with interior hoops and solid aluminum rim. This design was eventually chosen for the LRV as initially proposed by Boeing.

"The wheel development was instigated by the fact that under the temperature conditions, which in shade goes down to about −300 degrees Fahrenheit and in the sunlight of day goes up +250 degrees or so, rubber or plastic materials could not be used," Pavlics stated. "We had to invent an all-metallic but still flexible wheel. Since this was a manned vehicle going at a reasonable speed over rugged terrain, it had to provide the astronauts with a good ride quality. So, the wheel had to be flexible and have good flotation over the soft lunar terrain. That is how we started developing this all-metallic wheel.

"We tried many different types and different materials, and finally nailed down this configuration which was a flexible wire frame-type of wheel. The behavior of the wheel was like a low-pressure pneumatic tire. It was flexible and it had a good footprint over the soft terrain so it didn't sink into the soil. At the same time, it provided a certain amount of damping because the interwoven wires, as they deformed, had a friction at the joints, so it didn't bounce like a spring would. The other thing we had to be concerned about, because of the low gravity on the Moon, was that the wheel had to be designed to be very soft, to have a deformation under the static load of the vehicle. At the same time, the dynamic forces are, of course, the same on the Moon as everywhere else, so when you run into a rock or an obstacle, the impact force would be the same as it would be on Earth. That is why if you look at the wheel, which is kind of transparent because of the open wire mesh construction, you can see a secondary wheel inside which was made out of titanium spring material – the bump stop hoops. As the flexible part of the wheel deformed when it ran into an obstacle, it would engage this secondary hoop-type wheel and that would absorb the dynamic impact force.



The Control and Display Console of the Qualification Unit was clearly marked "Non-Flight." The inboard hand-holds with light colored grips were vital for properly seating on the Lunar Rover in 1/6 gravity in the astronaut's pressure suits. The left hand-hold also served as a mount for the Low-Gain Antenna, and the right hand-hold served as the mount for the 16mm Data Acquisition Camera (DAC). The Sun Shadow Device is in the stowed position to the right of the Heading Indicator. (NASA)

"The nominal static load on each wheel was about 67 pounds (147 kg) with the vehicle, astronauts and all the equipment on board," Pavlics added. "But when it ran into a rock, at say ten miles per hour (16 kph), the forces would be more than ten times as high, so we had to design the wheel for impact forces like that. We actually tested the wheel up to 1,000 pounds (455 kg) of force, which it was able to take. Because of the secondary wheel inside, it could be deformed all the way to contact with the secondary hoop wheel without any permanent deformation of the primary

wire mesh wheel. The wire diameter and material came about from stress analysis which was performed. If we used fewer spring wires, they would have to be thicker to support the same load, but if we had thicker diameter wires, at the same deformation, the stresses would be higher. So we optimized that and came up with a relatively small diameter, high-strength steel spring wire, so that the stress levels would be below the allowable level. This was really defined by fatigue properties. We tested the wheels over the equivalent of 120 kilometers, which was more than twice the expected usage."

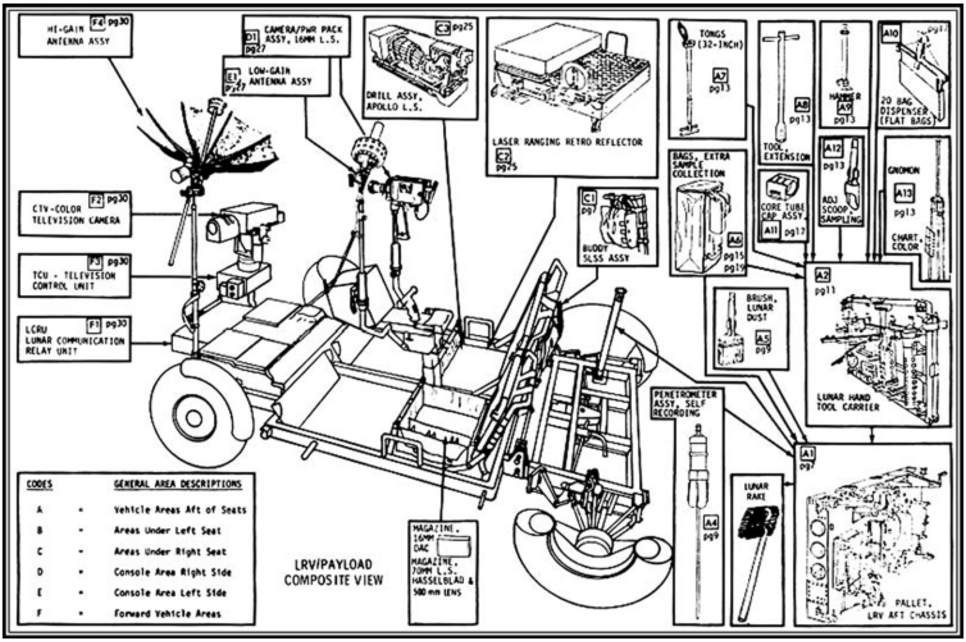
The wheel was manufactured by GM's Defense Research Laboratories using 0.84 mm diameter steel spring wire. The wire was cut to a length of 81.3 cm and then 800 of these wires were hand-woven in a special jig to give a seamless wire mesh that had 64,000 wire intersections. To this were riveted titanium tread strips in a specific chevron pattern, resulting in fifty per cent coverage of the contact patch. This, in turn, was riveted to a spun 2024-T4 aluminum alloy disc and rim. To prevent the collapse of the wheel under impact with lunar rocks, the wheel featured an inner frame, as mentioned by Ferenc Pavlics. This had a circumferential ring and hoop springs made of titanium. The resulting wheel assembly measured 81.3 cm in diameter and was 22.8 cm wide, but weighed only 5.5 kg.

The LRV employed Ackermann geometry steering. The wheels did not steer in parallel, but the innermost wheel in a left- or right-hand turn had a greater steering angle corresponding to its shorter turning radius. The RFP stated that the LRV would employ both front and rear steering as a redundancy in the event of either one failing. If this occurred, the failed steering could be locked in its center position to prevent drifting while the other steering system operated. The two steering systems were electrically powered through separate forward and rear steering motors with speed reducers and servo systems, and were mechanically independent of each other. The original steering rate specification was later changed to a higher rate as a result of feedback from the crews in the trainer. Steering was controlled, as was speed and braking, through the hand controller.

CREW STATION SUBSYSTEM

The Crew Station Subsystem included the folding seats, seatbelts, folding foot rests, hand controller, arm rest behind the hand controller, inboard and outboard hand holds, toe holds, floor panels, the Control and Display Console (CDC), and the wheel fenders. Much of the Crew Station Subsystem was refined as a result of Air Force KC-135 flights simulating $\frac{1}{6}$-G for astronaut training. The toe holds and hand holds in particular were essential in allowing the astronauts to properly ingress and egress the rover during these flights. The folding seats, inspired by aluminum beach chairs, were lightweight and folded into a compact envelope. Nylon webbing acted as the seating surfaces. The seat bottom could fold up to permit access to the stowage compartments under each seat.

The hand controller was a marvel of multi-function operation. The design of the hand controller was initially conceived as a pistol grip, and remained so well into the



The LRV was a complex spacecraft, as this illustration shows. (NASA)

LRV development program. However, astronauts John Young and Charlie Duke pointed out to Boeing and MSFC that the vertical pistol grip design was extremely difficult to use in a pressurized suit. The subtle movements of the wrist required to accomplish steering, accelerating and braking could not be achieved with desired results.

"We worked with the Marshall Space Flight guys on the way the hand controller worked," said Capt. John Young during an interview with this author in 2003. "They had designed it so that you moved it like a control stick in yaw with your wrist. In a pressure suit, you couldn't move your wrist a lot. The wrist would be so tired you wouldn't be able to drive after two or three minutes."

A late design change ordered just months before delivery of the first flight unit resulted in the amended horizontal grip that the astronaut could rest his hand on and which allowed him to use his forearm to perform the LRV functions. Inputs from the hand controller were sent to the Drive Control Electronics located in the forward part of the LRV. These interpreted the mechanical movements of the hand controller into the appropriate signals to change speed or direction, or to apply braking. Moving the hand controller progressively from its spring-loaded central position resulted in greater acceleration or steering angle. Pivoting the hand controller either left or right beyond a half-degree would commence steering. The hand controller could pivot nine degrees either left or right before encountering a soft-stop and progressive resistance to get ever-greater steering angles. Moving the controller rearward from its central position applied the braking action and moving it rearward

7 to 8 cm applied the parking brake. This could be released by moving the controller hard left. Reverse was achieved by the astronaut pushing up on a knob just below the grip and moving the controller rearward.

The Control and Display Console was the nerve center of the LRV. The panel was divided into two main sections. The upper section contained the navigation heading, speed and vehicle attitude information, the navigation gyro torquing and the system reset button; the lower section contained vehicle electrical power controls for batteries, drive and steering controls, and the systems temperature indicators. All vehicle information visible to the astronauts would be radioed in real-time to Mission Control. On top of the CDC was the Sun Shadow Device, which helped to determine the LRV heading with respect to the Sun and worked in conjunction with the directional gyro to indicate the LRV position for the navigation system. Visibility in the harshest conditions was vital, either in shadow or direct sunlight, so the panel itself was black with panel markings irradiated with promethium 147.

The fenders were vital to controlling dust, as tests had proved. Due to the compact envelope of the folded LRV, the front and rear wheels pressed against each other when stowed in the LM. Sliding fender extensions were designed to permit this contact and these were moved by the astronaut along their mounting rails and locked into their fully extended position after the rover was deployed on the Moon. There is an interesting story regarding details of the fender design. Eric Jones, respected author of the online *Apollo Lunar Surface Journal,* was contacted by Bill Kimsey, who was an engineer with Boeing during the Apollo years. He was closely involved with the design of certain aspects of the LRV as presented in Boeing's proposal to MSFC.

"There were quite a few of us sent from New Orleans to Huntsville to work on the proposal," Kimsey told Jones for the *ALSJ*. "One of the other fellows, Waine Borne, and I had been working together from 1961. We had gotten to be good friends. We both had Model A Fords that we had restored. The Model A has beads around the fenders. I was joking with Waine and drew a bead on the fenders of the Rover. The project manager asked me why I put the bead on the fender and I told him it was to stiffen the fender. The bead remained on the fender. Now it's sitting on the Moon. It is the same width as a Model A Ford. No one but the two of us really knew the story."

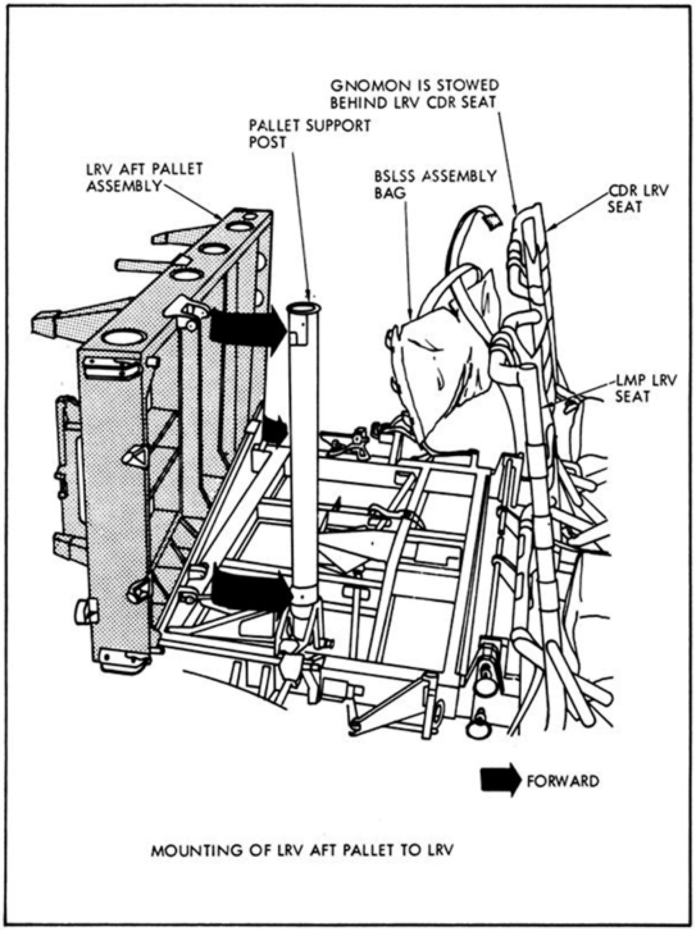
NAVIGATION SUBSYSTEM

When Boeing presented its concept for the LRV navigation system, Morea and his NASA team felt the system was overly complex and that with such complexity came the risk of potential failure. The astronauts could not afford to lose their navigation system, especially as there was no redundancy.

"From the standpoint of navigation," Morea said, "Boeing proposed a very complex inertial guidance platform for the vehicle that our engineers at Marshall felt was too sophisticated for the job to be done. By running a few simple tests at the Marshall laboratories, we came up with a concept we felt was a major improvement

[and which] we felt Boeing should consider. This system ultimately ended up being developed by Boeing."

The MSFC Astrionics Laboratory's Guidance and Control Division set to work to engineer a simple and utterly reliable navigation system. Working with the Sensors Branch, a dead-reckoning system was conceived, based on several years of previous study and investigation. The systems studied ran the gamut of simple direction finders to systems using satellite navigation. For the LRV, the system had to meet the same requirements as other subsystems, namely simplicity, reliability, light weight, ruggedness and low power consumption. In addition, it had to be relatively intuitive to minimize crew familiarity training, it had to retain navigation



The Aft Pallet Assembly was engineered and built by NASA to be mounted to the rear of the LRV in order to carry tools, lunar samples, lunar drill, core tubes, and small scientific experiment packages. A hinged gate was mounted to the Aft Pallet Assembly to secure tools and permit additional lunar sample bags. (NASA)

readouts in the event of power loss, and it had to be manufactured using existing technology. Functional requirements included navigation to a predetermined location, providing vehicle speed and distance traveled, and providing information to permit return to the LM by the shortest distance possible.

MSFC chose a system made up of a directional gyro, four odometers (one at each wheel traction drive), a signal processor, and devices for indicating vehicle attitude, position and speed. The gyro heading was initialized by using a simple Sun Shadow Device (mentioned in the Crew Station Subsystem) working alongside the vehicle attitude indicators. The Astrionics Lab built a prototype using essentially off-the-shelf parts and tested it at MSFC (including thermal-vacuum tests) and out at Flagstaff, Arizona.

In the tests in Arizona, MSFC technicians used a Jeep with blacked out windows, a television camera mounted on the hood and the prototype navigation system. Technicians in a station wagon followed the Jeep with the necessary equipment to act as "mission control." In this way the navigation system was validated and these tests proved the system could meet the Apollo mission requirements. Computer simulations confirmed the validity and performance of the design. The Directional Gyro Unit (DGU) was a Lear Seigler Model 9010. The Integrated Position Indicator (IPI) was manufactured by Abrams Instrument Corporation and was mounted on the left side of the Crew Display Console. The Signal Processing Unit (SPU) was engineered and built by Boeing. The Navigation Subsystem provided readouts for total distance traveled in kilometers for each EVA, based on the combined average from the four odometers, roll attitude of plus or minus 25 degrees, pitch attitude of plus or minus 25 degrees, heading (0-360 degrees), bearing to the LM (0-360 degrees), range to the LM (0-30 Km), speed in kilometers per hour, and the Sun angle provided by the Sun Shadow Device. The Apollo astronauts would refer to the navigation system almost constantly during their EVAs and relayed the information back to Houston during their traverses.

ELECTRICAL POWER SUBSYSTEM

The Lunar Roving Vehicle's Electrical Power Subsystem included two 36 VDC silver-zinc batteries, and wiring harnesses with connectors, circuit breakers, switches and meters. The batteries were engineered by Eagle Picher of Joplin, Missouri, and both minimum weight and power generation capability were the overriding parameters. The batteries used a lightweight magnesium case with a Plexiglas core, having twenty-three cells containing silver-zinc plates in a potassium hydroxide electrolyte. Each 27 kg battery was rated at 121 amp-hours. The electrical power subsystem was designed to have both batteries operating simultaneously. However, through the use of selective switching from the Control and Display Console, either battery could be called on to power the entire vehicle and its various systems if one of them should fail or need to be turned off.

The batteries were located in the forward chassis of the LRV, and benefited from a comprehensive thermal control subsystem which included thermal blankets and

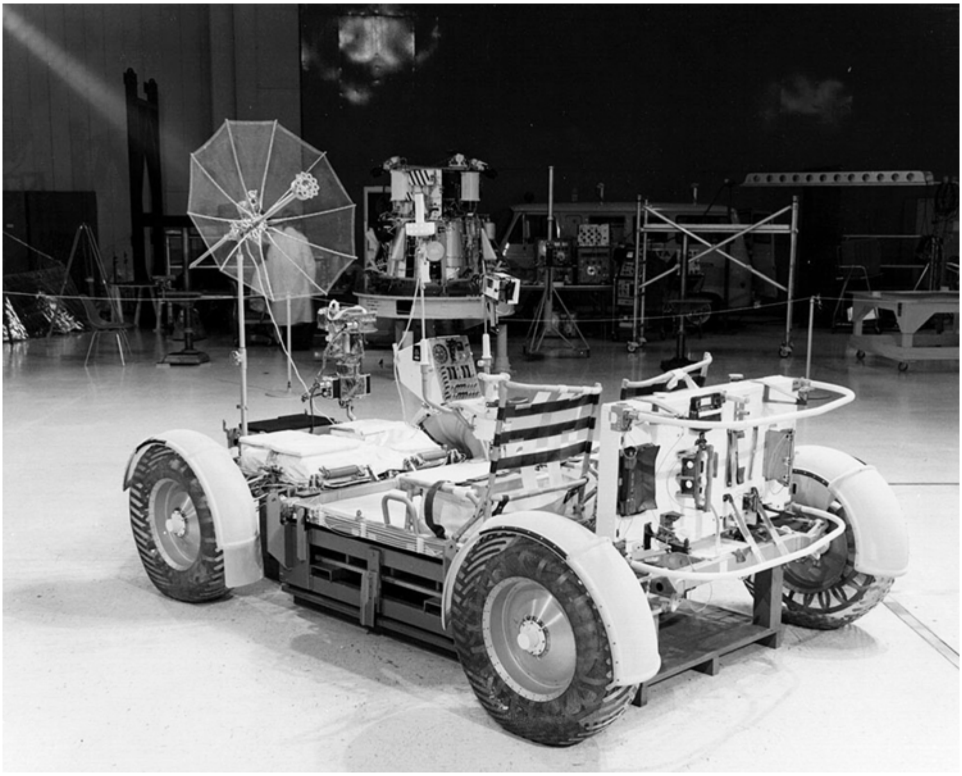
dust covers, explained below. Each battery had a relief valve to prevent excessive pressure building up due to high operational demands or prolonged elevated temperatures. Battery electrical capacity and temperature were monitored on the Control and Display Console.

Much of the data of the electrical power subsystem would be transmitted back to the Lunar Module, which would relay the data back to Earth and Mission Control. The electrical wiring harness was carefully routed along or within the LRV's chassis with particular attention paid to securing and protecting the wiring harness from damage due to fraying. One engineering aspect that had to be sacrificed due to weight limitations was a real-time battery monitor that could be read by the crew inside the Command Module, as was provided for other systems. After the batteries were installed in the LRV on the launch pad about three days before launch, they would only be monitored up to eighteen hours before launch. The astronauts venturing down to the lunar surface would not know if their rover would power up until it was fully deployed.

THERMAL CONTROL SUBSYSTEM

The function of the Thermal Control Subsystem (TCS) was to maintain all LRV components within specified temperature ranges during transit to and operation on the Moon. The TCS had to be engineered to function concurrently with the other subsystems of the LRV and to fit within an allocated weight limit of only 4.5 kg (10 lb). The LRV's electrical components could not be allowed to get too hot or too cold. This did not just apply to the LRV's operation on the Moon, but also had to be considered during launch to orbit, orbit of the Earth, trans-lunar flight, lunar orbit, descent to the lunar surface, and the period between the landing and the vehicle's deployment and utilization. Additionally, thermal control was required for the Space Support Equipment (SSE) which supported the LRV in the LM and allowed the LRV to be secured during transit and then deployed onto the Moon's surface. The mission profile that the LRV would be exposed to on the Moon would be during a 78-hour sunlit period of the lunar surface temperature cycle, which constituted the "lunar morning." This included solar elevation angles from 7 to 50 degrees, and lunar surface temperatures ranging from about 50 to 200 degrees Fahrenheit.

In addition to being able to operate on the Moon in $\frac{1}{6}$ gravity in a hard vacuum environment, the potential problem of lunar dust effects on vehicle surfaces and components was an important factor that had to be quantified for this vital subsystem. For this reason, Earth-based tests of this potential problem area and how to minimize its effects had been conducted in 1967. From these test results, it was established that the presence of lunar dust on surfaces would significantly increase absorbed solar heat. Tests of a variety of methods resulted in the selection of a dust removal brush, which appeared to work well in these Earth-based tests. Additional tests of the LRV wheel and fender assembly with a lunar soil simulant were conducted in a reduced pressure chamber in the NASA KC-135 airplane (Vomit Comet), flying special loops to simulate the expected $\frac{1}{6}$ gravity. It was verified in



The completed LRV Qualification Unit sits on its support fixture at Boeing. The Qual. Unit was required to thoroughly test and validate each system of the Lunar Roving Vehicle. (NASA)

these tests that the fenders were a vital element in directing the trajectory of lunar dust stirred up by the wheels, and would protect LRV components from exposure to the dust.

Based on all of these requirements, a semi-passive TCS was implemented for the LRV. This included the use of passive thermal control techniques consisting of selected radiation surface finishes, heat sinks, flexible thermal straps, multi-layer insulation, and low thermal conductance component mounts. The electronic components with the tightest temperature limits were grouped together in an insulated compartment (with dust covers) over space radiators in the forward chassis area. The insulation comprised fifteen layers of thin sheets of perforated aluminized Mylar, with interstitial layers of Dacron net in between and Beta cloth for protection on the outside. The exposed LRV crew station and mobility subsystem components were assumed to be dust covered on the Moon.

The TCS approached complete autonomy within the specified mission parameters. It imposed only one constraint with regard to parking between traverses and required only one astronaut interface at the end of each driving traverse to initiate the

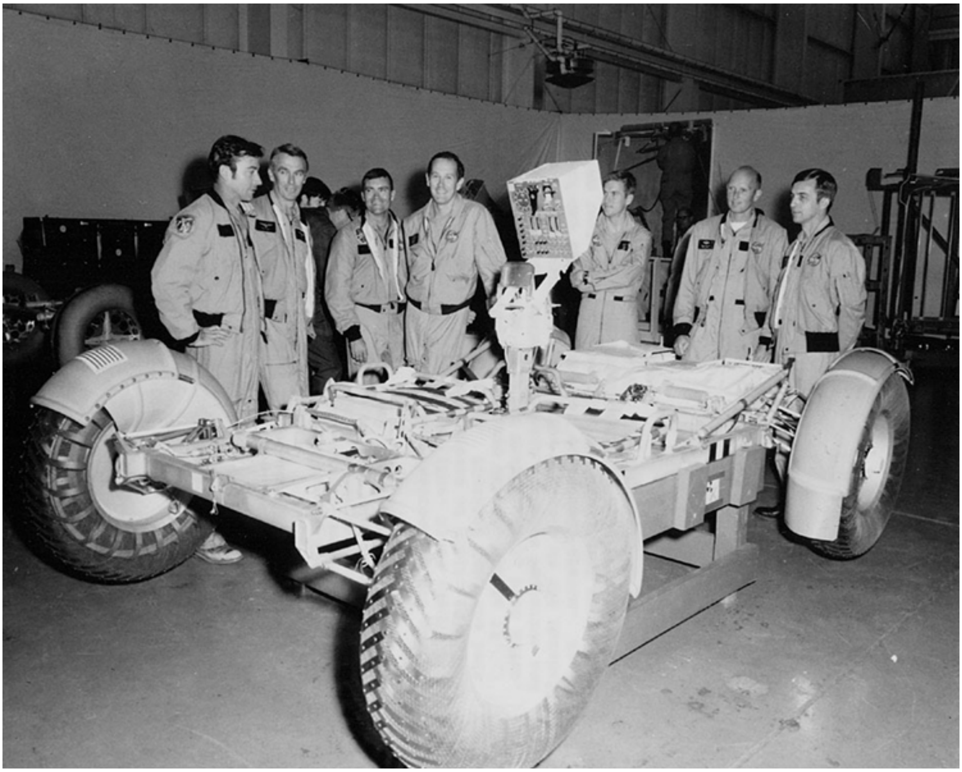
automatically terminated cooling of the electronics by opening the dust covers over secondary surface space radiators. The original intent was for the TCS to be totally autonomous and not require any interaction with the astronauts. For the electronics grouped in the forward chassis area, an enclosed ammonia boiler, like those ultimately used on the Space Shuttle Orbiter, was considered but was deemed too heavy.

During operation, the batteries would be a great heat sink for their own internally generated heat, and an additional heat sink for some of the other electronic components. Flexible thermal straps were designed and tested to enable heat to be conducted from the Signal Processing Unit (SPU) to Battery 1 and from the Directional Gyro Unit (DGU) to Battery 2. The Drive Controller Electronics (DCE) had to be positioned too far from the batteries for effective thermal strapping. Passive thermal "heat pipes", which are used extensively on present-day spacecraft, were not mature enough designs at the time of LRV development, so another heat storage and transfer method was needed.

Therefore, fusible mass "wax tanks" were used to store the excess heat generated in the DCE (7.7 kg of wax) and the SPU (4.9 kg of wax) during operation. The added advantage of these wax tanks was that they acted as "thermal dampers", maintaining the DCE and SPU at constant temperatures while the wax was being melted. The wax would then be solidified for re-use when the dust covers were opened at the end of driving on each EVA by exposing the thermal radiators on top of the wax tanks. It was planned to have the dust covers automatically close using bi-metallic spring actuators when battery temperatures reached a safe 45 degrees Fahrenheit ($\pm$ 5 deg. F.)

The job of ensuring that the TCS was up to the task fell to the engineers in the Propulsion Division of the Astronautics Laboratory at the Marshall Space Flight Center (MSFC). There were hundreds of engineers working on the LRV at NASA and its subcontractors, scattered across the United States. A fortunate few were recent college graduates who had the opportunity to work on one of the most challenging and exciting programs they would encounter in their careers. One of those young engineers was Ronald A. Creel. Ron had served as a cooperative education student in college and came to work full-time at MSFC shortly after the LRV program was launched in 1969. He was immediately assigned to the design and testing for thermal control of the LRV Mobility Subsystem. This involved working with the A.C. Delco Electronics Division of GM, which was in charge of development of the Mobility Subsystem. Creel was involved with the thermal vacuum testing of the LRV brakes, fluid damper, and steering system in the fall of 1970.

This was followed by computer simulation modeling and thermal vacuum testing of a ¼-scale mobility subsystem at the Boeing facility in Kent, Washington. Creel related, "We almost didn't get the LRV mobility system tested due to the overheating and failure of a ground test motor which was used to power the treadmill with obstacles, over which the LRV system was driven. We had to work extra long hours one weekend in order to rig up a coolant system using copper tubing and good old water. With the test system repaired, the mobility system test proceeded very well. The test technicians had a healthy skepticism about this young thermal engineer and his computer performance predictions for motor temperatures.



(from left) John Young, Gene Cernan, Fred Haise, Charlie Duke, Tony England, Gordon Fullerton, and Don Peterson pose with the LRV qualification test unit at the Marshall Space Flight Center. 1 November 1971

As we approached the maximum expected test operation period one night, the technicians skeptically asked me what the maximum drive motor temperature would be while we were out to dinner. I answered that my prediction was a maximum temperature of 254 degrees F. When we returned from dinner, the technicians verified that the maximum temperature had actually been 255 degrees F. They were not so skeptical about the young thermal engineer after that.''

Hugh Campbell, who was LRV Lead Thermal Engineer, felt confident in putting Creel to work on additional modeling and thermal vacuum testing of the LRV forward chassis. This would include the batteries, Signal Processing Unit (SPU), Drive Control Electronics (DCE), Directional Gyro Unit (DGU) – indeed anything electrical having to do with the LRV. In addition, human factors involving the surface temperatures that the astronauts would come into contact with were another critical issue. This was the ''time-temperature'' constraint for all surfaces which might come into contact with the astronauts or their extra-vehicular mobility units (suits and backpacks).

These and other factors went into the preparation of the software thermal models

used to help both in the thermal design of LRV electrical and other subsystems and also in verifying thermal performance for all expected storage and operating environments. Correlating these thermal models with the test data was very important and allowed these "clean" test models to be subsequently altered to match the expected operation on the Moon and to generate realistic temperature predictions. LRV surface optical properties (solar absorption and infrared emission) were regularly measured in order to adjust both the computer thermal models that took into account these factors and the internally-generated and externally-applied heat loads, to verify expected performance.

"A primary concern," according to Creel, "was to have the LRV thermal control system be responsive to the variations of driving and operation of the LRV's on the Moon and the need to fully support the astronauts during all nominal and contingency operations. We refined the thermal computer models for thermal control system verification and mission planning based on correlation with thermal vacuum test results. This included the full-up Qualification Test Unit tested in the vacuum chamber in Kent, Washington. There were dynamometers on each wheel and solar simulations at a Sun angle of sixty degrees, which exceeded the expected level for planned Moon missions. My thermal modeling for mission support was ultimately rewarded with receipt of the astronaut's 'Silver Snoopy' award. This was for simplifying a complex and cumbersome LRV thermal model into a much more responsive and useful thermal model for mission support."

COMMUNICATIONS SUBSYSTEM

The Communications Subsystem comprised two equipment packages: the Lunar Communications Relay Unit (LCRU) and the Ground-Commanded Television Assembly (GCTA). The LCRU included the electronic equipment enclosure at the front of the LRV, with an additional umbrella-like S-Band High-Gain Antenna and a Low-Gain Antenna. The LCRU was mounted in receptacles on the forward member of the forward chassis. The High-Gain Antenna and its stalk was mounted in a dedicated receptacle to the left of the LCRU, as was the GCTA to the right of the LCRU. The Low-Gain Antenna was installed in the left LRV handhold adjacent to the display console. The GCTA, (given the verbal acronym "gotcha" by NASA engineers), included the Color TV camera (CTV) and the Television Control Unit (TCU). The 16 mm Data Acquisition Camera, though technically not part of the Communications Subsystem, was installed in the right LRV handhold.

When the astronauts were underway in the LRV, communications were routed through their PLSS antenna to the LCRU, which would send the communication to the Low-Gain Antenna for transmission to and from Earth. When the astronauts parked the LRV for their station stop, the commander would align the High-Gain Antenna with Earth, and both voice communication and live video from the GCTA would be patched through that antenna.

The CTV camera that beamed live images from the LRV back to Earth was built by RCA at the Government and Commercial Systems Astro-Electronics Division

Astronaut Bob Parker positions the DAC on the LRV Qualification Unit at Boeing. Note that he is wearing EVA gloves. Parker served as Apollo 15 Support Team member and later as CapCom on Apollo 17 (NASA)

in Princeton, New Jersey. Formally known as the RCA Ground-Commanded Color Television Assembly (GCTA), it was specifically designed under NASA contract 9-11260 for use on Apollo 15, 16 and 17. The TV cameras used on Apollo 11, 12 and 14 had been engineered by Westinghouse. On Apollo 11, the TV camera was a slow-scan black and white camera operating at ten frames per second. Its TV images were ghostly, but it did record Neil Armstrong stepping onto the Moon, and some other images as well. The Apollo 12 mission saw the first use of the Lunar Surface Color Camera, but the TV camera was inadvertently pointed at the Sun, frying the SEC imaging sensor. Apollo 13 was unable to land on the Moon and though the LSCC was used in a limited fashion on Apollo 14, the images were confined to the landing site and were less than desired. The new GCTA was vastly improved and more sophisticated in its capabilities, and provided high quality color images of the astronauts' operations on the Moon.

"The camera on Apollo 15 was a brand new camera, top to bottom, including the imaging tube which was specially developed for that project," said Sam Russell, an RCA engineer closely involved with the camera's development. "RCA top

management felt they had quite a stake in this. The company considered itself first with color television, and they wanted to gain back some ground they felt they had lost with Westinghouse having produced the cameras for the previous lunar landings. The GCTA had a silicon intensifier target imaging tube and it was immune to high overload if it was pointed at the Sun. We had to run performance tests of the camera looking at the Sun for a long time, and it withstood that. It was one of the requirements after Apollo 12 where the camera burned out.''

Both the LSCC and the GCTA employed a Silicon Intensifier Target (SIT) and a field sequential color wheel to generate color television images. The GCTA featured the addition of the Television Control Unit (TCU) that provided an azimuth and elevation mount for the color television camera which permitted manual or Earth-controlled television coverage from the LRV. It also had a lens modified to provide motor-driven iris and zoom operation.

``The guy who really came up with the motor control idea for the TV camera was Bill Perry,'' said Ed Fendell, who operated the TV camera during the Apollo 15, 16 and 17 missions. ``Bill was an engineer over in the Telecommunications Division of Engineering at JSC. He came up with the idea of the capability of controlling that camera.''

In function, the TCU received a command sub-carrier signal from the LCRU mounted on the LRV and could execute commands for azimuth and elevation movement of the camera, zoom, iris control, automatic light control and power functions. The TCU azimuth and elevation pedestal allowed the camera to pan 214 degrees to the right and 134 to the left, achieving nearly 360 degrees of combined movement. The range of elevation from horizontal was 85 degrees upward and 45 degrees downward. The TCU also managed transmitter and voice sub-carrier control with the LCRU, as well as accepting the camera video signal, adding a test signal and routing the combined video to the LCRU for transmission to Earth. The zoom lens of the camera was a specially modified assembly manufactured by Pierre Angenieux in Paris, France. The 6 $\times$ 12.5 mm zoom lens was designed with an f-stop range from f/2 to f/22 and a 6:1 zoom range.

As with many other electrical components of the LRV, thermal control of the camera and TCU was of prime concern. The camera featured a second surface mirror on top of the unit, as well as thermal blankets over the remaining surfaces. Thermal control of the TCU was achieved by the use of side radiators on the lower housing which held the electronics. Remaining portions of the TCU were also covered with thermal blankets.

``We did thermal vacuum testing, as well as vibration and acceleration testing which simulated the mission,'' Russell recalled. ``We had a huge thermal vacuum chamber in East Windsor, New Jersey. We also had to test every piece of equipment in a 100 per cent oxygen environment, regardless of whether it would be inside or outside the Lunar Module, as a result of the Apollo 1 fire. I was involved in a lot of simulations where I had built up a model of the lunar scene and tried to light it to get the dirt to look about the way the lunar dirt would look, which was very dark. Ultimately, I helped NASA set up a big simulation in Houston where we were mixing sand and lamp black together.''

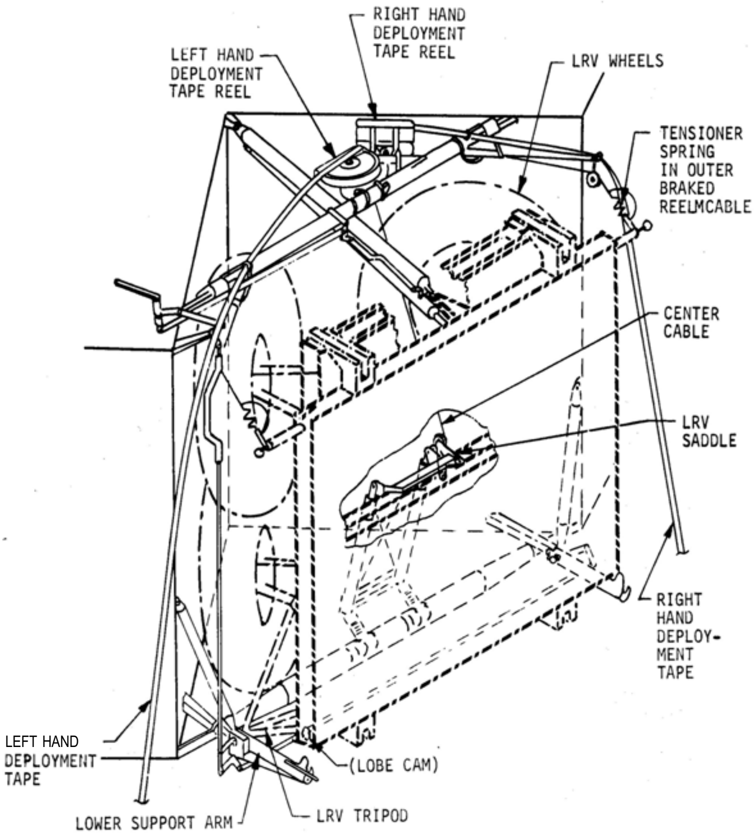
The camera and TCU would be stowed aboard the Lunar Module in the Mechanized Electronics Stowage Assembly (MESA) during the flight to the Moon and landing. The camera was connected electrically to the LM by a 35 m cable and its cradle oriented toward the LM ladder to permit live TV images as the astronauts descended to the lunar surface. There were four operational modes for the GCTA; two involved interface with the Lunar Module and the other two with the LRV. In the LM MESA Mode, the CTV remained in its Stowage Mount Assembly in the MESA. The TV circuit breaker was switched on before the astronauts left the LM and the mission commander would deploy the MESA prior to descending the ladder, which brought the CTV into position to allow millions of TV viewers on Earth to watch the astronauts descend to the lunar surface. In the LM Tripod Mode, the CTV was released from the Stowage Mount Assembly in the MESA and mounted on its tripod on the lunar surface by one of the astronauts with its 35 m cable connected to the LM. This would permit viewing of the deployment of the LRV and the lunar surface experiments packages. The LCRU/LRV Mode moved the complete GCTA to the Lunar Rover, where it was mounted on a staff in the forward part of the LRV. A one-meter cable was then installed between the CTV and the TCU, and a longer cable from the TCU to the LCRU on the Lunar Rover. The final mode was the LM Liftoff Mode, where the LRV was parked a designated distance from the LM with the CTV positioned to record liftoff of the ascent stage, with camera panning controlled from Earth.

This remarkable system permitted recording of virtually all mission aspects of Apollo 15, 16 and 17 except for those times the LRV was on the move. Because of the superb images the GCTA beamed back to Earth, the missions themselves were enhanced. The GCTA was the "eyes" of Mission Control and the scientific teams on Earth. It also made it possible to record the last three lunar missions for future generations to watch in wonder.

STOWAGE AND DEPLOYMENT SUBSYSTEM

Considerable thought, engineering and testing went into the development of the Lunar Roving Vehicle (LRV) Stowage and Deployment Subsystem. This subsystem design had to preclude premature deployment under the violent forces and loads that would be encountered during the Saturn V launch and potential hard LM landings on the Moon. A premature deployment inside the Saturn V or at LM landing could potentially have caused LRV and/or LM structural damage and proven disastrous. Yet the system also had to be "astronaut (user) friendly" to reliably facilitate easy deployment of the LRV once the LM was safely on the lunar surface and lunar exploration (astronaut egress and subsequent science gathering) had begun.

Boeing proposed, and NASA accepted, an automatic means of LRV deployment early in the LRV program. Early deployments of a $\frac{1}{6}$ gravity LRV simulator showed that the dynamics of rapid LRV automatic deployment using hinges, springs and latches was such that no single deployment of the LRV was repeatable. That made it unreliable. In November/December 1969, Boeing performed qualification testing of



A fully-automatic deployment system was deemed too complex and NASA chose to go with a semi-automatic deployment system with the involvement of the astronauts. (NASA)

their automatic deployment system, during which the $\frac{1}{6}$ gravity LRV simulator was deployed from a simulated LM in all extreme corners (eight positions) of the expected lunar deployment envelope. The Boeing automatic system successfully deployed the $\frac{1}{6}$ gravity LRV in all these positions, but no single deployment from any of these Lunar Module positions could be repeated exactly.

Eugene Cowart had joined Boeing in 1956 and was one of the senior engineers on the LRV program. He was promoted to chief engineer for the LRV later in the program. He was present during a presentation of the proposed deployment system to MSFC Director Eberhard Rees.

"The deployment was a complicated proposition, because it had to deploy from the Lunar Module in various angles," Cowart remembered. "The original design had it coming out like a switchblade knife. When you pulled the lever the springs literally unwound. We had a big presentation to show that thing. Dr. Eberhardt Rees and

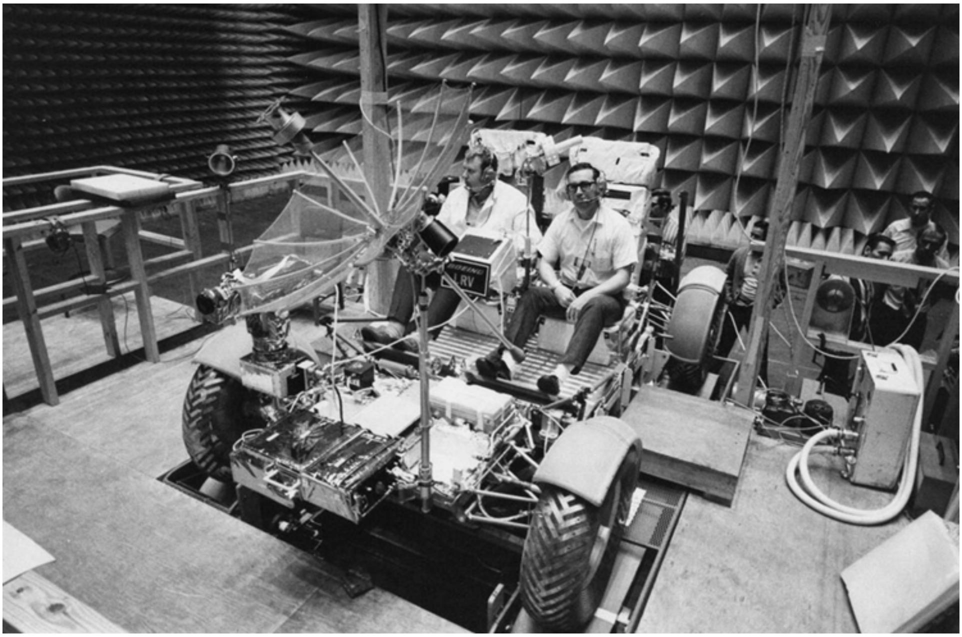
others came over to see it in the Hick Building in Huntsville where the mockup was at the time. I remember someone pulled the lever, it made a hell of a noise and hung up halfway down. And I remember Rees saying, 'I don't think it will work like that!' And I said, 'Oh no, it's not going to work like that.' In any event, we changed that so it was lowered down."

Due to the non-repeatability of the automatic deployment system, Dr. Eberhardt Rees, then Director of the Marshall Space Flight Center, instructed NASA's Structures and Propulsion Laboratory to assist Boeing in the qualification (design changes) of the automatic deployment system and also to design a 'backup' deployment system for the LRV in case the automatic system could not be qualified. MSFC structures and propulsion design personnel designed a semi-automatic LRV deployment system. The design consisted of adding a pulley on the end of a shaft with a worm gear to the existing Boeing-designed deployment system. This design meant that the LRV could be deployed under total astronaut control; i.e., the astronaut could stop the deployment at any point to assess the deployment process and make corrections to the hardware as required. The MSFC design was demonstrated to John Young and Charles Duke using a plywood wall and a $^1/_6$ gravity LRV simulator. They pulled the deployment tapes and successfully lowered it to the floor. MSFC personnel also designed a tool for them to use to unlatch the wheel/chassis latch pins in case any of the pins got stuck during the deployment.

As "users", astronaut involvement was of crucial importance. They would be called upon to make sure the LRV was properly deployed and readied for its traverses on the Moon, so the easier it was for them to do this critical portion of the mission, the greater the likelihood of mission success. Engineering and Management discussions over the pros and cons of a fully automatic deployment versus a semi-automatic deployment emphasized the deployment repeatability of the semi-automatic system. The automatic system simply encountered too many chances for failure and this would effectively have scuttled the LRV mission. Astronauts John Young and Charles Duke were actively involved in many aspects of the LRV's design where it required astronaut interface.

"It seemed to me" stated Charlie Duke, "that crew involvement in the rover's deployment would be better and we would have better control with the semi-automatic deployment as opposed to no control of the deployment with the fully automatic system. So we helped the LRV design engineers do that." With astronaut concurrence and encouragement, the MSFC semi-automatic deployment design was selected.

The LRV was designed to be stowed in a very confined space (one of the four bays on the Lunar Module). This meant that the LRV had to be "folded in on itself" by having all four wheels in a "tucked in" position and then the forward and aft chassis, including the wheels, folded in over the center chassis. On the lunar surface, the LRV had to be safely lowered from the LM bay, the forward and aft chassis had to unfold and lock, and the four wheels had to "un-tuck" and latch before the LRV was in contact with the lunar surface. After contact, the LRV had to be disconnected from the LM/deployment system. Then, further LRV set-up could commence in preparation for the LRV mission. The goal was to have the LRV deployed in



Boeing technicians conduct electromagnetic compatibility tests on the Qualification Test Unit at the Manned Spacecraft Center in Houston, Texas. (NASA)

fifteen minutes. It had to be able to deploy with the LM tilted as much as 14.5 degrees from its vertical axis in any direction, with the bottom of the descent stage anywhere from 35 cm to 160 cm above the lunar surface. The support and deployment system included lower support arms, with latches, cables, pulleys, pin retraction mechanisms, telescoping tubes, a push-off rod, and straps or deployment tapes. The deployment sequence began with the mission commander, (standing on the LM ladder) pulling a handle and releasing the three pins which secured the LRV to the LM. The spring-loaded push-off rod then moved the still-folded LRV away from the top of the LM storage bay by about 12 cm, where it was stopped by two steel cables and the main chassis rotation pins were latched into the lower support arms. The telescoping tubes provided mechanical support and control to ensure that the LRV was deployed clear of the LM. To prevent the LRV from inadvertently rolling under the LM, the telescoping tubes were "one way", having locking latches to preclude telescoping inwards.

The commander would then descend the ladder and would be joined by his crewmate. Together, they would deploy the LRV from the LM. One astronaut would pull on a nylon tape that would slowly lower the LRV to the lunar surface while the other astronaut would monitor the deployment and pull on his deployment cable attached to the LRV chassis, if required, to assist in the outward motion of the LRV from the LM. At roughly 45 degrees, release pins on the aft chassis automatically pulled. The aft chassis then deployed and the wheels and suspension unfolded and

locked into position. At approximately 73 degrees, the center chassis would unlatch from the support arms and the forward chassis (attached to the telescoping tubes) would deploy and lock into position. The astronaut to the left of the LRV would then pull on that deployment tape, allowing the forward portion of the LRV to be lowered to the lunar surface. Then a lanyard would be pulled to release the telescoping tubes from the LRV. The astronauts could then move the LRV away from the LM and orient it for driving away. There were "barber pole" indicators to verify that the chassis locking pins were fully engaged.

Many vibration and deployment tests were performed at Boeing and MSFC to ensure the system worked properly and reliably. Astronauts practised Lunar Rover deployments at Kennedy Space Center and at MSFC using the deployment trainer. The best justification for all this testing is the fact that there was never a failure of any LRV to deploy on the lunar surface, nor throughout its subsequent use to gather science and samples. All three LRV missions were a total success and the astronauts of these missions were elated with the use and performance of the vehicle.

On 6 April 1971, a final Lunar Roving Vehicle Design Certification Review presentation was made to MSFC management. As Boeing chief engineer for the LRV, Eugene Cowart spoke on the vehicle's design and systems, which took up the majority of the review. The initial requirements for the LRV were shown, along with the actual targets achieved. The required weight was 400 pounds (181.9 kg); actual weight was 493.81 pounds (223.9 kg). The operational capability of 78 hours was achieved. The required top speed was 16 kph; actual speed was 14 kph. The desired range was 120 kilometers; actual would be 92 kilometers. The target payload capability of 440 kilograms was exceeded; the LRV's actual payload capability was 482 kilograms. It met or exceeded the slope climbing and stability requirements, as well as the crevasse and obstacle negotiation parameters. Most impressive was the delivery of Flight Unit No. 1. It had a target date of 1 April 1971 for delivery to NASA; it arrived two weeks early, on 14 March 1971.

LRV BOUND FOR THE MOON WITH APOLLO 15

"When this program was all over," said Morea, "although Boeing did indeed – as we suspected they might – overrun about 100 per cent on the cost, the remarkable thing was that there were but eight change orders over the entire life of the program. It was seventeen months from the time we signed the contract at Boeing to the day we delivered flight hardware – man-rated – to the Cape. I am very proud of that accomplishment, and Boeing and GM deserve a lot of the credit for stepping up to the plate and making it happen."

"It was a rush program," Pavlics stated in defense of GM's efforts in the development of the LRV, "and at the peak of activity, we had as many as 400 people working just on the GM side of the program. Of course, we did a lot of testing because it was a man-rated system. Therefore, all the reliability and quality requirements which applied to Apollo also applied to this Lunar Rover."

Morea believed that Boeing's original financial number for delivering the LRV

was inadequate, and MSFC had secretly budgeted accordingly. The final cost of the LRV program – nearly $40 million – was very close to what MSFC was prepared to pay to get its vehicle. The world only had to wait for the LM *Falcon* to land at Hadley-Apennine and for LRV-1 to help unfold the mysteries that awaited. However, there was an unseen cost, one that didn't show up on the financial books. Many engineers and program managers involved with all aspects of project Apollo can recall to this day the toll it took on their health, their family lives, and in many cases their marriages. At the same time, however, they also recall those hectic, taxing years as some of the most rewarding of their lives. Pavlics spoke for many when he recalled the frantic activity at GM's Defense Research Laboratories in Santa Barbara and the rush to develop, test and deliver the crucial subsystems of the LRV.

"The most rewarding part for me," Pavlics clearly remembered, "was that the teamwork was so excellent. Everyone was pulling for the project, for its success. I didn't hear a single complaint about overtime or working on weekends. Everyone was enthused and excited about the program. I think that made it possible to complete it in such a short time."

With the acceptance of LRV-1 for Apollo 15 by Marshall Space Flight Center, Boeing proceeded with completion of LRV-2 for Apollo 16 and LRV-3 for Apollo 17. The speed with which the Lunar Roving Vehicle was proposed, designed, built, tested and delivered was indeed unprecedented within the Apollo program. By comparison, the astronaut Personal Life Support System (PLSS) took seventy months and the Apollo spacesuit took sixty months. In the end, the LRV performed up to and beyond expectations and accomplished the goal of vastly expanding the manned exploration of the Moon.

Training for the Moon

John Young squinted through his sunglasses into Meteor Crater outside Flagstaff, Arizona on a cool January day in 1963. With him were Neil Armstrong, Frank Borman, Charles "Pete" Conrad, Jim Lovell, James McDivitt, Elliot See, Thomas Stafford and Ed White. They were guided and briefed by Dr. Eugene Shoemaker and Charles Marshall from the United States Geological Survey (USGS) Branch of Astrogeology and Surface Planetary Exploration. This geologic field trip to Flagstaff was the very first for the new group of astronauts destined for the Apollo missions, but training for them to identify surface features and formations on the Moon actually began within a year of President John Kennedy making his bold decision for the United States to land astronauts on the Moon in May 1961.

THE USGS BRANCH OF ASTROGEOLOGY

In 1960, Eugene Shoemaker, one of the Survey's pre-eminent geologists, founded the Branch of Astrogeology in Menlo Park, California. Two years later, he moved the Branch's headquarters to Flagstaff, Arizona, one of the richest geologic locations in the entire United States. Flagstaff is situated at the foot of the San Francisco Peaks, a 3,850 m high dormant volcano that is surrounded by the extensive San Francisco Volcanic Field. This proved an ideal starting point for field training the astronauts to learn basic geologic procedures – to identify varied rocks and minerals by their appearance and structure, volcanic formations on the surface and much more. In 1962, NASA selected the U.S. Geologic Survey to provide training to the first class of astronauts. This was a victory for Shoemaker, who had initially encountered stiff resistance from Dyer Bainard Holmes, the head of NASA's Office of Manned Spaceflight. In 1965, Dr. Gerald G. Schaber would begin working for Shoemaker's fledgling Branch of Astrogeology in Flagstaff, just two years following that very first astronaut geologic field trip to Meteor Crater in 1963.

"Shoemaker was the one who first got the astronaut geologic training program started and was subsequently instrumental in convincing NASA to allow the astronauts to do some actual science while on the lunar surface," Schaber recalled

Eugene Shoemaker (center) established the Branch of Astrogeology within the United States Geologic Survey (USGS) in 1961. He is shown here with Ray Baston (right) and Elliot Morris discussing lunar mapping. Comprehensive mapping of the Moon and geologic field training of the Apollo astronauts by the USGS contributed immeasurably to the success of the manned lunar missions. (USGS)

vividly. "Initially, some in NASA just wanted the astronauts to go without picking up a single rock. If it hadn't been for Shoemaker, they wouldn't have. He was a pain in their side because he wanted them to do some *science* while they were up there. We were doing astronaut training with our own geologists in spacesuits out at Hoppi Buttes and Meteor Crater east of Flagstaff starting in 1963. The first field test using actual spacesuits took place in June 1964 outside of Flagstaff, at Sunset Crater and Bonita Lava Flow in the Sunset Crater National Monument."

Holmes left his position at the MSC in September 1963. His replacement, George Mueller, was more sympathetic to the idea of lunar geologic science and established the Office of Manned Space Science within the Manned Spacecraft Center. Formal classroom geologic training of the astronauts began at the MSC in Houston, Texas in 1964, under the direction of veteran USGS geologist, Dale Jackson. Classroom sessions were also conducted by Al Chidester, Don Wilhelms, Gordon Swann and Dan Milton, who introduced the astronauts to basic geologic concepts and such specific celestial activities as impact cratering. Jackson realized that test pilots and

In 1965, the Branch of Astrogeology in Flagstaff received the Mobile Geologic Laboratory built by General Motors in Santa Barbara, California. It was built to help the USGS develop methods and procedures for manned lunar exploration for the Apollo program. (USGS)

astronauts needed classroom teaching, but felt just as strongly that he had to get them from behind their desks and exploring the surface of the Earth to gain better knowledge, which they could apply once on the surface of the Moon. In March of 1964, Jackson organized the first field trips to the Grand Canyon in Arizona. The two trips to the Canyon included a who's who of the NASA astronaut corps: Buzz Aldrin, William Anders, Charles Bassett, Alan Bean, Eugene Cernan, Roger Chaffee, Michael Collins, Walter Cunningham, Don Eisele, Theodore Freeman, Richard Gordon, Russell "Rusty" Schweickart, David Scott, Clifton Williams, Wally Schirra, Deke Slayton, Gus Grissom, Gordon Cooper, Ed White, Frank Borman, Jim McDivitt, Jim Lovell, Pete Conrad, John Young and Tom Stafford. Other geologic trips that year were scheduled for Marathon Basin and Big Bend

Park in Texas, Philmont Boy Scout Ranch near Cimarron in New Mexico, San Francisco Volcanic Field outside Flagstaff, Newbury Crater at Bend in Oregon, and Valles Caldera in New Mexico.

That was also the year that a young graduate geology student, Harrison "Jack" Schmitt, wrote to Eugene Shoemaker in Flagstaff seeking a position in the Field Office. Shoemaker had written to Schmitt at exactly the same time after reviewing Schmitt's USGS exam results. Schmitt had been introduced to Shoemaker several years before while the senior geologist was tasked with mapping the Moon. After joining the USGS, Schmitt assisted Shoemaker in the geologic mapping of the Moon while also leading the Lunar Field Geological Methods project in Flagstaff. When NASA announced it was looking for scientist-astronauts in the later months of 1964, Schmitt decided to apply. He would have a bit of a wait to learn NASA's decision, however, since over one thousand interested individuals applied.

Shoemaker was actively searching for the best and the brightest geologic minds to join the USGS Branch of Astrogeology and to contribute to what would unarguably be the greatest feat of manned exploration ever undertaken. This was no secret to those in the geologic community in the United States. Don Wilhelms was working on this doctorate degree in geology at UCLA when he was interviewed by Shoemaker in 1962. Shoemaker was very impressed with Wilhelms' knowledge, but waited until the graduate student was on the verge of receiving his PhD before accepting his application to join the USGS. With his eye fixed to the Lick Observatory telescope on Mt. Hamilton in California, Wilhelms worked earnestly to contribute to the mapping of the Moon. He became actively involved in training the astronauts both in the classroom and the field. The Moon became Wilhelms' life and he joined a slowly growing cadre that included Dale Jackson, Gordon Swann, Elliott Morris, Don Elston, Al Chidester and Dan Milton at Menlo Park.

Throughout the early to mid-1960s, the USGS Branch of Astrogeology became a magnet for aspiring geologists, drawn by the lure of mapping the Moon, expanding our overall knowledge of Earth's nearest celestial body and actively participating in training the men who would travel there and explore its surface. Despite the fantastic nature of what had to be accomplished to get astronauts there, have them safely land on and then explore the Moon, and return them to Earth, the geologists at the USGS, and most of all Shoemaker himself, had supreme confidence that it could be accomplished. They were also very much aware that they would become active participants in one of the most historic events of the twentieth century. The group would eventually include, among others, Margaret Cox, Raymond Batson, Norman Bailey, Michael Carr, David Dahlem, Kenna Edmonds, Richard Eggleton, Richard Godson, Henry Holt, Keith Howard, Martin Kane, Thor Karlstrom, Ivo and Barbara Lucchitta, John McCauley, Harold Masursky, Henry Moore, Joseph O'Conner, Robert Regan, David Roddy, Lawrence Rowan, Gerald Schaber, David Schleicher, Hal Stephens, Robert Sutton, George Ulrich, and many more individuals. This geologic brain trust was not confined to PhD geologists, but also drew in cartographers, photographers, illustrators and other related disciplines all vital to the work that would go on at the USGS in support of the Apollo program and planetary exploration. Like the hundreds of thousands of other Americans

The *Explorer* was built by the Branch of Astrogeology Field Test Support Group in 1967 as the first vehicle to be used by Apollo astronauts for simulated lunar exploration training. Rutledge "Putty" Mills is shown here driving *Explorer* over a block lava flow north of Flagstaff, Arizona. Note the pistol grip vehicle controller (USGS)

involved with project Apollo, this period in their lives would become the most rewarding of their entire careers.

"The spirit of the Project Apollo can be best described by something that Gene Shoemaker, founder of the U.S. Geological Survey's Branch of Astrogeology, told his new recruits in the early 1960s," recalled Schaber. "He said 'You will be asked to far exceed your own perceived capabilities, in order to make the seemingly impossible a reality'."

LUNAR VEHICLE TESTING AT THE USGS

In December 1963, Shoemaker appointed John McCauley as co-investigator for the Surveyor Lunar Roving Vehicle (SLRV). This was a small robotic vehicle about one meter long and half-a-meter wide and weighing approximately 45 kg. NASA conceived this vehicle to be soft-landed on the lunar surface, and to then, as its name stated, survey the surrounding area, take stereoscopic images and beam them back to Earth, as well as performing other functions. NASA contracted with Bendix Corporation and General Motors (GM) to build prototypes, which would be tested by the USGS. In May 1964, McCauley and his team took the Bendix and GM vehicles out to the Bonita Lava Flows and Sunset Crater north of Flagstaff for testing. McCauley's group, dubbed "The Rover Boys," included Ron Scott from Caltech, Noel Hiners (who would later become director of the Goddard Space Flight Center), Ray Batson and Roy Brereton. Supervising the test with McCauley was L.V. Divone of the Jet Propulsion Laboratory in Pasadena, California. The articulated, six-wheeled GM vehicle did quite well in traversing the rugged terrain, but the Bendix vehicle with its rubber tank-like treads performed poorly. However, the ability to traverse rugged terrain was just one capability the vehicle had to have. The SLRV also had to perform a given series of other functions at precise distances. McCauley and his team felt that the vehicles as they were configured would not effectively perform site certification. The team wrote a report to NASA stating as much, and after evaluating the report, the space agency cancelled the SLRV program.

NASA was looking much more seriously into manned lunar vehicles, as described in Chapter 1, and looked to the USGS to test them in Earth-surface conditions that simulated those on the Moon as closely as possible. The first of these vehicles to arrive in Flagstaff in April 1965 was the Lunar Mission Development Vehicle, built by General Motors' Defense Research Laboratories. It was identified on the side as the Mobile Geologic Laboratory, or MOLAB for short. The MOLAB acronym, however, also applied to several vehicles built by Grumman and Bendix. MOLAB was conceived while NASA believed that there would be two Saturn V launch vehicles to get men and machines to the Moon. This particular vehicle was designed to accommodate two astronauts in a pressurized environment with full accommodations and would permit extended traverses on the Moon lasting days at a time.

Don Elston was head of the Manned Lunar Exploration Division of the USGS Branch of Astrogeology, and he coordinated the field tests of this vehicle to establish feasibility studies of geologic equipment designed for use on the lunar surface (such

Astronauts Charles Duke and John Young photographed at the Nevada Test Site with *Explorer* during March 1972. The vehicle is fitted with updated Crew Station control panel and T-handle vehicle controller. (USGS)

as the gamma ray spectrometer unit), and suited astronaut interface with MOLAB. The vehicle was almost three meters wide, three meters high and roughly five meters long. MOLAB had fuel, drinking water and provisions that could permit the two occupants to operate the vehicle for two weeks in the Arizona landscape. Its operating speed was 6 kph, but it could operate on flat terrain up to 33 kph. It could climb slopes as steep as 45 degrees and was stable traversing a 30-degree slope. GM's MOLAB was built at a cost of $600,000, a staggering sum for such a vehicle in 1965. It was used in tests for only two years before NASA cancelled the long-duration Apollo mission profiles in 1967. The vehicle was later transported to Marshall Space Flight Center in Huntsville, Alabama.

By July 1965, the Branch of Astrogeology's Office of Manned Lunar Exploration Systems had appointed specialized project chiefs in various disciplines in support of Project Apollo. John M'Gonigle was Acting Project Chief of Apollo Geological Methods; Gordon Swann was Project Chief of Apollo Extension Systems Methods; Joseph O'Connor was Project Chief of Advanced Systems Geological Methods; P.G. Ables was Project Chief of Scientific Task and Biogeological Investigations; E.C. Phillippi and Henry Holt were Project Chiefs of Lunar Field Imaging Systems; and Rutledge "Putty" Mills was Project Chief of Lunar Vehicle Systems. Mills had come to the Branch of Astrogeology courtesy of GM's Defense Research Laboratories in Santa Barbara, and came to Flagstaff originally to watch over and maintain GM's

MOLAB, and to assist in the vehicle's various field tests. It didn't take Shoemaker and others in Flagstaff long to realize that Mills would be an asset to the Branch of Astrogeology and he eventually accepted the offer to work there.

The conventional wisdom at NASA during the mid-1960s was that Project Apollo would incorporate two Saturn V launch vehicles for each mission to the Moon. In this way, bigger and heavier lunar exploration vehicles could be used. Bendix proposed a Lunar Roving Vehicle that would be landed on the Moon prior to the crew arriving. This vehicle would have remote control capability if the crew had to land too far away from it. To test this concept, NASA asked the Branch of Astrogeology in Flagstaff to build a test vehicle for crew training and to test geophysical equipment, navigation and vehicle remote control. The construction of this purpose-built vehicle was supervised by Putty Mills with assistance from Bill Tinnin and Dick Wiser. It was given the name Explorer. It was a perfect example of form following function, built at the lowest possible cost. To have four-wheel drive capability, the drive train and V8 gasoline engine of a Jeep pickup were used. A custom steel tubing frame and suspension was built to house this drive train. To give the vehicle the necessary ground clearance and traction, the wheels and tires from a Cub Tractor were employed. The vehicle driver sat up front and steering was controlled by a single servo-actuated joystick to the right of the driver, but Explorer could also be controlled with a TV camera vision system that could be viewed

The Geologic Rover, called Grover, was a low-cost yet highly effective training vehicle used in USGS astronaut mission EVA planning and training for the J-missions of Apollo 15, 16 and 17. Note the integrated Personal Life support System (PLSS) backpacks, which permitted training by the astronauts in shirtsleeves. (USGS)

remotely. It had a navigation system that could plot its direction and a gyro compass from a surplus military aircraft. Built in 1967, Explorer was not only used for varied tests by the Branch of Astrogeology during the rest of the decade, it was also used by the crews of Apollo 16 and 17 prior to their missions.

The Apollo crews continued to participate in geologic field training by the Branch of Astrogeology, in addition to the other mission training they had to undergo. During 1965, the astronauts had trained at the Nevada Test Site, as well as Hawaii, Alaska, Iceland, Zuni Salt Lake in New Mexico and the Pinacate Volcanic Field in Mexico. Many of the geologic sites selected by the USGS were visited several times by rotating teams of Apollo astronauts during the remainder of the decade. In 1969, assigned crews and their backups for Apollo 11 through Apollo 14 began their own specialized geologic field training. In May 1970, the Apollo 15 prime crew of David Scott and Jim Irwin and backup crew of Richard Gordon and Jack Schmitt began mission-specific geologic field training. Schmitt had indeed been selected as one of the six scientist-astronauts to train for Apollo missions, and his selection is covered in Chapter 5. The Apollo 15 crews trained in the Flagstaff crater field at Cinder Lake, as well as in Alberta, Canada, the San Juan Mountains in Colorado, Buell Park in Arizona and in Northern Minnesota. In November 1970, the Apollo 15 crew began training with a new vehicle built by the Branch of Astrogeology. Its official name was the Geologic Rover, but it was nicknamed Grover for short.

A scratch-built trainer

In April 1970, Putty Mills received a phone call from Donald Beattie, NASA's program manager of Apollo Lunar Surface Experiments. Beattie explained that the LRV 1-G Trainer would not be completed in time for Apollo 15 mission training and planning that was set to start in roughly ninety days. He wanted to know if the Branch of Astrogeology could construct a reasonably accurate trainer for the astronauts to use. Mills assured Beattie that if he could get drawings of the LRV, he could build a trainer in time for Dave Scott and Jim Irwin to begin their mission training. Relieved, Beattie directed Mills to fly to Huntsville, where he would be briefed on the LRV and given full cooperation by Boeing. Once in Huntsville, Mills was given complete blueprints of the LRV and took many Polaroid photographs of the various subsystems under design development. Mills flew back to Flagstaff and pulled together the team that would build Grover. He called in Bill Tinnin and Dick Wiser, who had both worked on building Explorer.

Mills realized he couldn't build a 1-G trainer in a mere ninety days, but he did feel that his team could build a rugged training vehicle that would closely resemble the LRV using readily available steel tubing, surplus or salvage parts and some clever imagination. Within the limitations of the vehicle he had to build, Mills also wanted Grover to be electrically powered. He was familiar with numerous different types of electrical motors, and he drew on his experiences during World War II to seek out a source for the vehicle's drive motors. After doing some research, Mills settled on the landing gear motor from a B-26 bomber from a military surplus dealer in California This motor had a built-in gear reduction of 45:1 and each cost a mere $12.50. To power the motors, Mills chose four standard off-the-shelf six-volt lead-acid batteries,

Astronaut David Scott (center) points out features on a map to Jim Irwin while sitting on Grover during a training exercise at Cinder Lake Crater Field in Flagstaff, Arizona in November 1970. To Scott's left is Harrison "Jack" Schmitt, who would later be selected as Lunar Module Pilot for Apollo 17. (USGS)

mounted in the forward portion of the vehicle's chassis as with the LRV. Torsion bar suspension would provide the most compact envelope and after looking at several different automobiles, he settled on the torsion bar suspension used on the British-built Morris Minor he found in an auto salvage yard in Phoenix, Arizona. Grover would even have its own directional gyro system. Mills selected an electrically-driven gyro from a retired Frontier Airlines passenger aircraft and modified it to the necessary specifications. The design team also drew from the electrical servo-actuated steering system used on Explorer and modified this for use on Grover as well.

Working from the Boeing blueprints, Mills established Grover's wheelbase and wheel track. Wheels and tires were selected which would place the center chassis section and seats at the same height as the LRV. With these key dimensions, work began at the East Flagstaff fabrication shop at 1720 East Street. Chrome-Moly alloy steel rectangular section tubing was cut and welded to replicate the fixed forward, center and aft chassis. Front and rear control arm pivot points were welded to the

Jim Irwin and David Scott with Grover near the Rio Grande Gorge during a field training exercise in March 1971. The location was selected for its similarity to Hadley Rille, which they would explore during their mission to the Appenine region of the Moon on Apollo 15. The astronauts are wearing the non-functional versions of the PLSS and their Hasselblad cameras. (USGS)

chassis, and the control arms with drive motors bolted into place, followed by the wheels with tires. The seat frames were fabricated from aluminum with foam bottom cushions and built-in mockups of the Personal Life Support System mounted to the seat backs so the astronauts, working in their shirtsleeves, were in the proper position relative to the various parts of the vehicle. Reasonably accurate mockups of the control panel, High-Gain Antenna, Low-Gain Antenna, Color TV camera and 16 mm Data Acquisition Camera were added later and completed the appearance of Grover. Beattie had kept in routine contact with Mills to monitor Grover's progress and, true to his word, Mills and his team completed the vehicle within the necessary ninety days.

The first vehicle test of the Grover took place on 21 August 1970 at the Cinder Lake crater field outside Flagstaff. On 1 September, astronauts John Young, Charles Duke, Fred Haise, Tony England, Gerald Carr and Bill Pogue, along with other personnel from the Manned Spacecraft Center, flew to Flagstaff to participate in geologic field training in northern Arizona and southern Utah. The following day, they paid a visit to Putty Mills at his USGS fabrication shop to check out the new vehicle built by the Branch of Astrogeology. Grover was taken to a vacant lot across the street from the shop and the astronauts were given the chance to drive it. All agreed that Grover would be a superb vehicle to aid in mission simulation. Most

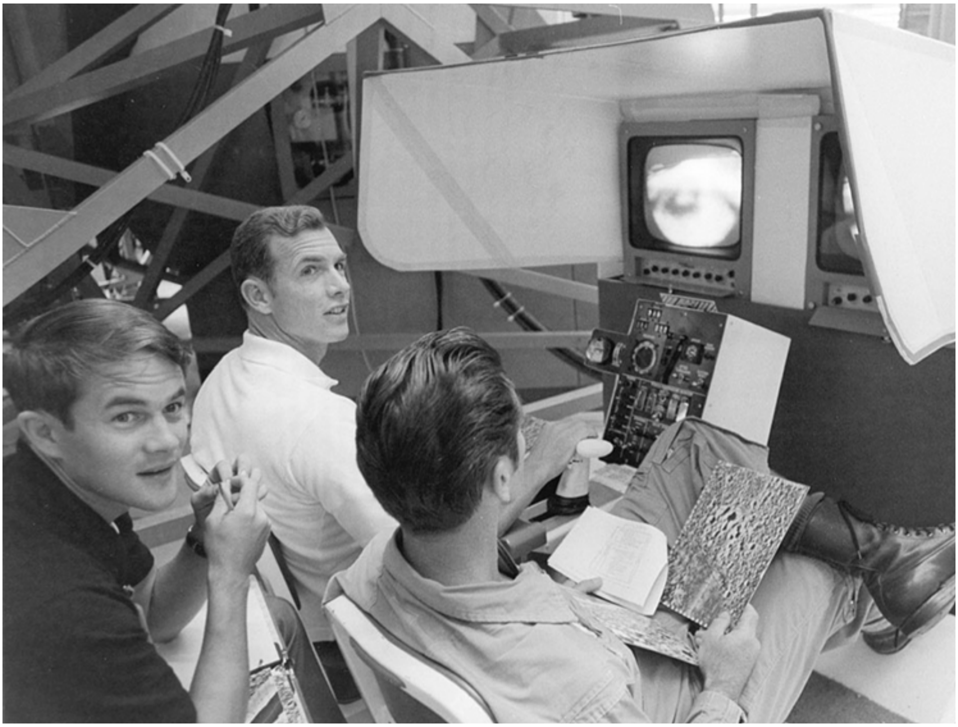
amazing of all, Mills and his team had succeeded in building Grover for less than \$2,000.00.

TRAVERSE PLANNING AND MISSION GEOLOGIC TRAINING FOR THE J-MISSIONS

In October 1969, USGS geologist Gordon Swann submitted his proposal to NASA to be Principal Investigator on the Geology Experiment Team for Apollo 14 and 15. When Swann's proposal was accepted, he asked Gerald Schaber to be one of his co-investigators for those missions. This specifically involved traverse planning and subsequent mission geologic training and traverse map production. With the addition of the LRV for Apollo 15, traverse planning and training grew considerably. Swann asked Schaber and other Branch of Astrogeology geologists to perform geologic mapping of various training sites in Arizona, Hawaii, Nevada and other locations using stereo aerial photography. This was meant to simulate the mapping of the early Apollo lunar landing sites using photographs taken by Lunar Orbiter. This effort was significant because several of the co-investigators who mapped the geology of the training sites would also map the actual traverses for the Apollo J-missions. On a three-day field test from 30 September through 2 October 1970 at the Merriam Crater test site north of Flagstaff, Grover was used to evaluate lunar surface maps in various scales, over a 15 km proposed traverse planned for Apollo 15. Weeks later, Gerald Schaber, along with Jim Head of Bellcomm, presented the preliminary Apollo 15 walking and LRV traverses to the Surface Working Panel group at the Manned Spacecraft Center in Houston, Texas. Dave Scott and Jim Irwin were present.

"They asked me, 'OK, Jerry, why are we going there?'," Schaber recalled when queried about a specific area at the Hadley-Apennine region. "And I told them, 'We are going out to St. George Crater because it is a large crater, it intersects the Rille, and it's on the bottom of the slope from Hadley Delta. So you want to sample that, go up the slope of Hadley Delta to try to find anorthosite, and you want to go over to the Rille and look for layering.' We mapped the landing sites in various scales – 50,000:1, 25,000:1 and 12,500:1 – and the Survey's Cartography group in Flagstaff produced the maps. We didn't have computers back then, so every time they wanted to make a change in the traverse, we had to recalculate the oxygen usage, the logistics – the whole thing – all by hand. We also had to have contingency traverses for walking if the LRV failed to work. We had rules from the mission operations people about how much time leeway we had. You couldn't get them back to the LM with only two or three minutes of oxygen left. Dave Scott was one helluva sharp geology type and listener."

Dave Scott had flown with Neil Armstrong on Gemini 8 in March 1966 and served as Command Module Pilot on Apollo 9 in March 1969 – a complex ten-day mission to validate many aspects of the Lunar Module in low-Earth-orbit. He had been involved with geologic field and classroom training for six years, and he took the utmost interest in the traverse planning meetings which would establish the places he and Irwin would explore on the Moon.



Dave Scott and Jim Irwin sit before a traverse simulator in this July 1971 photo. Behind the astronauts sits Dr. Joseph P. Allen, who would be their CapCom on Apollo 15. (Courtesy NASA)

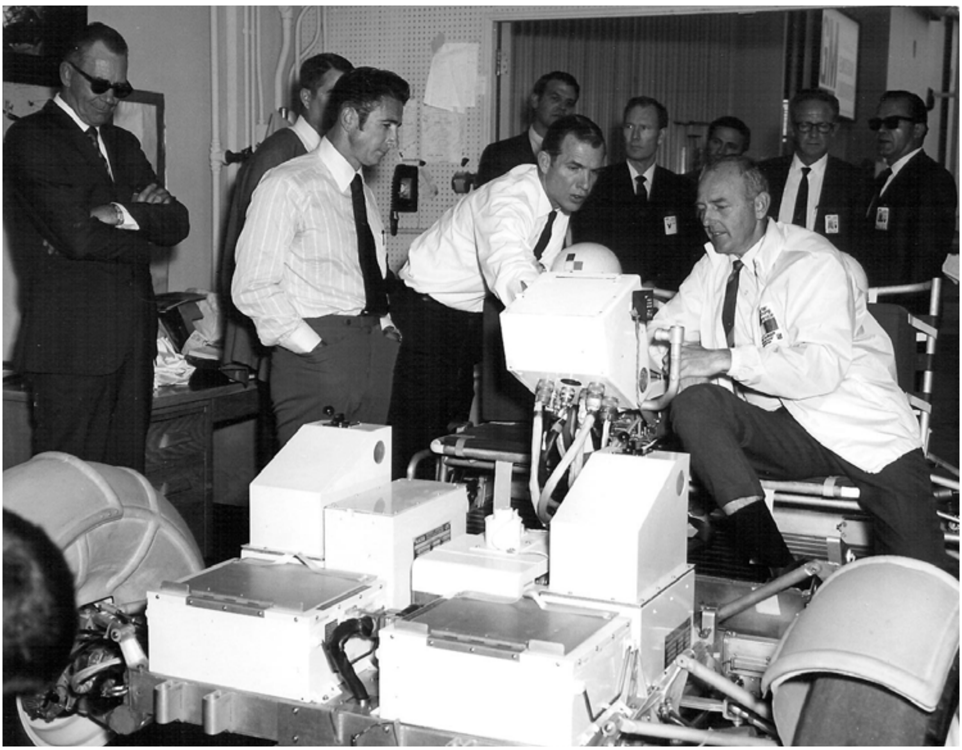
"The real reason behind the rover," stated Scott, "was so we could plan traverses that covered the distance and a variety of geology that would be expected on the Moon, because if you didn't have wheels, you'd have to walk and you couldn't cover the distance. We tried to simulate our geology traverses during training as closely as possible to what we'd actually do on the Moon. My philosophy was always do everything on the Earth as absolutely close as possible as you can do it before you get to the Moon. Then you learn things about how long it takes you to get from one place to another, what the CapCom might be doing in between and what the geologists might be doing. We actually simulated a day's work by having the Grover. We had to spend a lot of time on walking traverses because we didn't know whether the rover would work on not. So we had two sets of traverses, even on our Cuff Check List, one set of which was on the rover and the other set would be if the rover didn't work. If, for example, it worked on the first EVA but didn't work on the next two, we had very detailed backup traverses planned for walking. That was one of the challenges of the first J-mission. There was a high level of confidence, obviously, but nobody knew whether it was really going to work, and we had to achieve the geology goals. So, the planning included both the driving traverses and walking traverses, and we did that in our training too."

Sam Romano (standing), Dr. Mieczyslaw G. Bekker (center) and Ferenc Pavlics pose with the GM-built 1-G Trainer outside the Delco Electronics Division in Santa Barbara, California. The 1-G Trainer incorporated numerous changes from the LRV in order to operate in Earth's gravity. Note the pneumatic tires with wire mesh and metal chevrons applied to the tire's surface. (Sam Romano)

A key individual in the geologic training of the Apollo astronauts involved in the upcoming J-missions was Leon T. Silver. Like Shoemaker, Schmitt and many others geologists who became deeply involved in the Apollo program, Silver was a graduate of Caltech. Silver first met Shoemaker in the summer of 1948 when they both worked at the USGS on a government program searching for uranium sources for possible nuclear weapons development. Silver became specialized in isotopic geochemistry. He did not become actively involved in the lunar program until he was asked to build a lunar sample laboratory at Caltech, where he was a professor. Silver watched the crude television transmission from Apollo 11 as Armstrong and Aldrin collected their lunar samples during their brief historic landing on 20 July 1969, knowing he would be among the first to have the opportunity to examine and date some of the samples they brought back. In the meantime, Harrison Schmitt had seen an opportunity to focus the geologic training of the Apollo astronauts even more and when he approached Gene Shoemaker and discussed how this might be accomplished, Shoemaker recommended Lee Silver at Caltech – his former professor – as the ideal candidate.

Teaching the astronauts to be geologists

Silver knew these astronauts had acute observation skills, but he wanted to direct their attention toward enhancing the scientific return of their missions by honing their ability not only to identify the types of rocks they might find, but also to determine how they might have been formed. Silver wanted to train them to be able to verbalize what they saw for the sake of the scientific teams back on Earth. He also recognized that the astronauts already had full plates, as far as training was concerned, so he had to convince them of the value of this concentrated form of training, if they would willingly fit it into their training schedule. James Lovell and Fred Haise, scheduled for the Apollo 13 lunar landing, agreed to undergo several days of Silver's training, accompanied by their backup crew of John Young and Charlie Duke. In September 1969, Silver and one of his post-doctoral students took the two Apollo crews to a remote desert area some 37 km southeast of Palm Springs, California, near the Orocopia Mountains. Harrison Schmitt joined the group as well. Silver had a marvelous ability to get the astronauts to imagine themselves at a lunar



Jim Irwin and Dave Scott are being briefed on the 1-G trainer by Don Jessup at the General Motors Delco Electronics Division, formerly known as the Defense Research Laboratories, in Santa Barbara, California. GM had built numerous lunar exploration developmental vehicles for NASA since the early 1960s, and engineered and built the LRV's Mobility Subsystem for Boeing. (Sam Romano)

landing site and to observe their surroundings, identify and then describe in detail what they saw. All the astronauts enthusiastically felt that this informal training session was most worthwhile. The crew of Apollo 13 never landed on the Moon due to a catastrophic failure in the Service Module, but they returned to Earth safely. Silver did not conduct a similar training session with the crew of Apollo 14, that task being assigned to another geologist. However, with Apollo 15, Silver worked closely with Dave Scott and Jim Irwin and the two astronauts proved to be superb studies.

While the prime and backup crews for Apollo 15 had been performing mission-specific geologic training since May 1970, the first use of Grover in mission training took place on 2 and 3 November. The location was Merriam Crater and Cinder Lake Crater Field at Flagstaff, Arizona. Astronauts David Scott and Jim Irwin took part, along with Dick Gordon and Harrison Schmitt. The crews conducted location, sampling and crater avoidance exercises at Cinder Lake, while a 5 km traverse was performed at Merriam Crater's maar, lava flows and ash-fall deposits. When Grover wasn't being used for crew traverse training, it was pressed into use for LRV equipment validation. In December 1970, Grover was used to simulate the field of view of the Ground-Commanded Television Assembly (GCTA) using a 35 mm still camera, and to assist in recommending procedures for increasing the geologic return for the J-missions.

"The reason we spent so much time working geology and training on geology," David Scott recalled, "was so that we'd be able to make judgments on the Moon and use that flexibility. The more we learned, the more able we were to adjust where we were going to achieve the basic objectives. And, of course, we didn't really know what the surface looked like until we got there because of the lack of high resolution photos. The reason we went out on these many, many days with Lee Silver and Jim Head and all those guys was to get tuned up in areas similar to Hadley (such as Taos), such that when we got there we could make the necessary adjustments. At the same time, the geologists back in mission control in the back room – the same guys that trained us – had this communications link where we understood what we were saying to each other."

By the end of 1970, the USGS employed over 200 personnel in support of Apollo, and now included the Branch of Surface Planetary Exploration. In 1971, a total of twenty-eight geologic field training exercises were scheduled and included the crews of Apollo 15, 16 and 17. But not all them involved Grover or Explorer. These training exercises had to be coordinated with the Manned Spacecraft Center in Houston because of the training schedule for other aspects of the missions, which took place every day of the week and were planned months in advance. The USGS was not only involved with the training, traverse planning and lunar surface map production, the geologists also assisted in drafting the preliminary science reports and the sample return reports after each mission. The workload and pace were unrelenting, but it was at the same time exhilarating. The ability to accomplish all this was down to the men and women Shoemaker had selected to work there.

The geologic field training of the astronauts had evolved over the decade from a fairly rudimentary protocol to a sophisticated and specialized training program. Once Harrison Schmitt was accepted into the astronaut training program, he also

Apollo 15 backup crew members Dick Gordon (left) and Harrison Schmitt train in the "rock pile" with the 1-G Trainer at Kennedy Space Center during July 1971. Gordon is adjusting the 16mm Data Acquisition Camera while Schmitt attaches a Sample Collection Bag to Gordon's PLSS. Good view of the Lunar Hand Tool Carrier in the open position. (NASA)

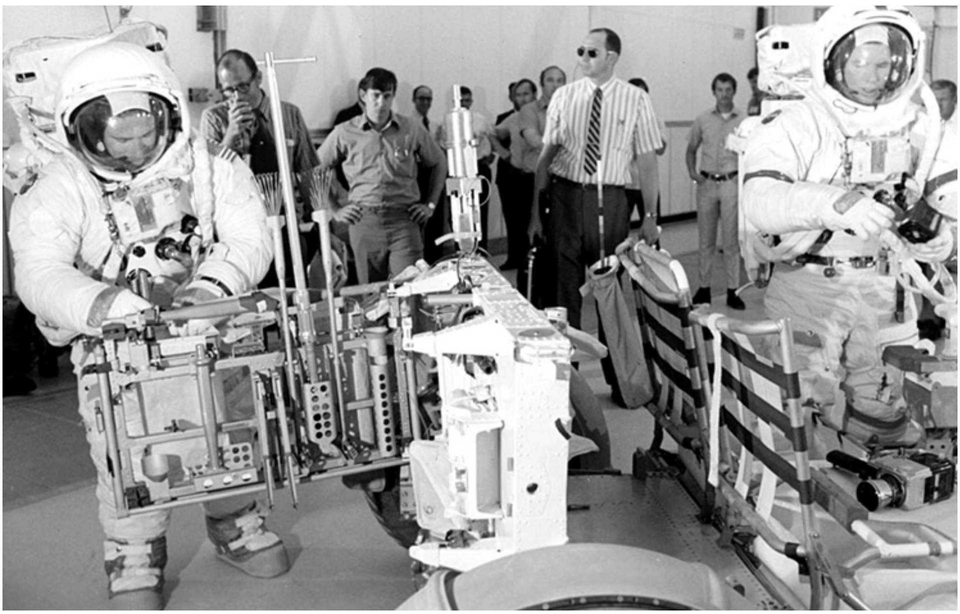
worked within the Astronaut Office to improve the methods of geologic field training for the Apollo crews, which eventually included himself as Lunar Module Pilot for Apollo 17. In a pre-mission press conference, he explained at length the evolution of the geologic training program at NASA that involved not only the USGS, but universities as well.

"It started out, as you might expect, based largely on the experience geologists had had with training students, generally the common students at the university level," Schmitt explained. "And, before too much time had passed, it became fairly clear that this way was not an effective way to train highly motivated, very intelligent men for the specific task of exploring the Moon in a geologic sense. The problem was, over the space of time, you could expose them to geology [but] you couldn't be concentrated enough so they would get a fundamental background like that normally given to a university student. It had to be interspersed with many other activities. And there were never any final examinations – nothing that would keep iterating and reiterating the principles that were being taught. So it became obvious

that the normal way of teaching, that is the classes and occasional field trips, was not efficient. It was effective and it brought to the surface considerable interest for the field of geology and science in general, but it was not getting to the meat of the problem of exploring the Moon in a geologic sense.

"But those of us who were concerned about the problem," Schmitt continued, "gradually brought into the program some of the very finest professional teachers we could find at the university level in geology. It turned out that these people, as is usually the case with very fine teachers, were also some of the top scientific minds, in their particular areas especially, that we could have found. And the combination was unbeatable. I'm thinking of people like Leon Silver at Caltech, Richard Johns at Stamford, Bob Sharp at Caltech, Jim Hayes at Harvard. These are the kind of people that we found, who could give the type of geological information we needed in training, in the context of what the lunar problems were. They treated the geometric and philosophical problems that we were going to deal with in geology on the Moon. They treated them, again and again, within the context and the kinds of constraints that a man would be dealing with on the Moon, and this turned out to be a much more efficient way to train. Each trip could build on the last trip. We were not only learning procedures, but we were learning geology at the same time."

The field training of the Apollo 15 and Apollo 16 astronauts during March 1971 was typical of the thorough training conducted that would help to ensure the success



The 1-G Trainer was used indoors at KSC for training to configure the LRV after deployment. Jim Irwin (left) is standing behind the Lunar Hand Tool Carrier of the LRV Aft Pallet Assembly. Dave Scott is holding a 70mm film canister for the Hasselblad camera on the right-hand seat. (NASA)

of the missions on the Moon. Between 10 and 12 March, David Scott, Jim Irwin, Dick Gordon, Harrison Schmitt, Joe Allen and Robert Parker were accompanied by Lee Silver, William Muehlberger, V.L. Freeman, Gordon Swann and M.H. Hait to the Rio Grande Gorge outside of Taos, New Mexico, which had been selected to simulate the perceived conditions with the Hadley Rille on the Moon. Geologists William Phinney and Gary Loftgren from the Manned Spacecraft Center also participated in the test. Putty Mills and William Tinnin brought Grover and the prime crew conducted two four-hour traverses, with real-time mission support as the crew gave geologic descriptions of their findings. On 29 and 30 March, the crew of Apollo 16 was in Flagstaff for training trips to Merriam Crater and the Cinder Lake Crater Field. The prime crew conducted eight-kilometer traverses in Grover, with Anthony England, standing in for backup crew member Edgar Mitchell, in the Explorer. These simulated traverses were backed up by a full contingent of USGS and MSC personnel who provided "mission back room" support as would happen during the mission to the Descartes region of the Moon, including evaluating, reviewing and monitoring the progress of the astronauts. Emphasis was placed on the craters, block fields and regolith stratigraphy that the crew would conceivably encounter on the Moon. A geophysical debriefing took place after the end of the second day's traverse.

Grover was proving its worth in the mission traverse training of the Apollo 15, 16 and 17 crews, but it was only one aspect of the LRV training that took place many months prior to their actual missions. Training also took place with the 1-G trainer and deployment trainer at Kennedy Space Center in Florida, simulation training at the Manned Spacecraft Center in Houston, Texas and even $\frac{1}{6}$ gravity training aboard NASA's infamous "Vomit Comet."

ENGINEERING THE 1-G LRV TRAINER

The 1-G LRV trainer was built by GM's Delco Electronics Division in Santa Barbara. Of necessity, it had numerous differences required for operation on Earth. Whereas the LRV was designed to operate on the lunar surface having $\frac{1}{6}$ the gravity of Earth, the 1-G trainer had to, in effect, be reverse-engineered to withstand six times its originally designed load and stress parameters, and to take into account other factors. The 1-G trainer had no requirement for deployment with folding forward and rear chassis, so the entire chassis was engineered and subsequently built to be fixed and rigid. The aluminum wheel rim was configured to accommodate pneumatic tires. GM engineered heavy duty wire mesh wheels for the 1-G trainer, but these were rarely used. The traction drive for each wheel used 34 VDC motors and a three-stage planetary gearbox instead of harmonic drive; these traction drives were not hermetically sealed. Specific thermal sensors were used on the gearbox to provide overheating indicators on the control panel. Wheel decoupling was simulated on the 1-G trainer to duplicate the LRV-to-crew interface. To properly brake the vehicle, GM designed hydraulically-actuated disc brakes for each wheel which were controlled through the hand controller. Torsion bars were installed only on the lower control arms.

Dave Scott is shown training with the core sample drill at Kennedy Space Center. The drill was kept stowed in the A2 Pedestal and the core tubes in the A2 Pedestal Bag to the right of the Aft Pallet Assembly on the 1-G Trainer. (NASA)

The 1-G trainer employed a continuously-operating steering motor actuated through the hand controller that energized counter-rotating particle clutches. Decoupling of the steering could be simulated, like the wheel decoupling. The hand controller operated in the same manner as the LRV with the same degree of movement for vehicle control regarding vehicle speed, steering and braking. The batteries differed on the 1-G trainer, being rechargeable 34 VDC nickel-cadmium batteries. Both batteries had to be used during operation of the 1-G trainer. Battery temperature was maintained using thermostatically-controlled fans and no thermal blankets were used. The navigation system was identical to the LRV and although calibrated for the wire wheels, the pneumatic tires were nearly identical in diameter so the losses were negligible. Changes to the crew station included the addition of seat cushions and floor panels of flat aluminum plate instead of beaded panels. Thermal control of this trainer was accomplished primarily through convection into

the atmosphere, with fan motors used on key components rather than the more sophistical system used on the LRV, as described in Chapter 1. The LRV was designed for an actual gross payload of 436 kg, or 73 kg on the Moon, whereas the 1-G trainer could sustain 362 kg of payload. The 1-G trainer also had its own maintenance schedule and this was outlined in Boeing's Lunar Roving Vehicle Operations Handbook.

TRAINING AT THE KENNEDY SPACE CENTER, FLORIDA

Training for the J-missions at KSC in Florida involved the 1-G trainer in a simulated crater and boulder field near the Operations and Checkout Building, as well as indoor training with the Deployment Trainer. The 1-G trainer was used for rover equipment configuration setup. Florida had no rocks even remotely resembling what might be encountered on the Moon that might be used in training, so Jerry Sevier in the Engineering Office of the Manned Spacecraft Center in Houston contacted Gordon

John Young (seated) and Charlie Duke train on an early Crew Station mockup during November 1970. The position of the mockup high-gain antenna, TV camera, low-gain antenna, and 16mm data acquisition camera are reversed in this photo. (NASA)

Swann at the USGS about obtaining an adequate quantity of suitable rocks to use in the training area at the Cape. With the help of Lee Silver, Swann arranged for a railroad gondola car to be loaded with anorthosite rocks from the San Gabriel Mountains near Pasadena, California, and two other gondola cars to be loaded with cinders from cinder cones in Flagstaff, all to be shipped to Kennedy Space Center. The crater and boulder field at KSC, nicknamed the "rock pile," was configured to facilitate sample taking and identification, as well as core sample drilling. The Cape has always been known for its exotic wildlife and snakes took considerable pleasure in hiding themselves among the rocks. Before training, personnel from KSC had to be sent out each day to check for snakes and remove any that had established residence there.

"We trained with the 1-G trainer down at the Cape," recalled John Young in an interview with this author. "We had a rock pile down there and a large place we could explore. The object was to go along and do the same kind of field stops that we would do on the Moon at about the same places, and pick up and examine the rocks."

John Young and Charlie Duke train with Grover at the U.S. Naval Ordnance test Range near Ridgecrest, California during a field training exercise in November 1971. Grover is shown without fenders since dust was much less of a problem on Earth than it would be on the Moon. (Courtesy NASA)

Prime and backup crews trained at the Cape during any given week, but not in the same locations at the same time.

"Backup crews trained on different days from the prime crews," said David Scott. "We might spend one day out on the rock pile with the rover while the backup crew was in the simulators. It was how the support teams could best support us in the various exercises. Training with the 1-G trainer at KSC involved only procedural things. In other words, where you put the tools, how you align the antenna, that sort of thing. It wasn't to teach us how to drive. It taught us what instruments to look at, who does what with the tools, how to get on and off, turning the TV on and off – that sort of thing. It was really a procedures trainer rather than trying to teach us to drive."

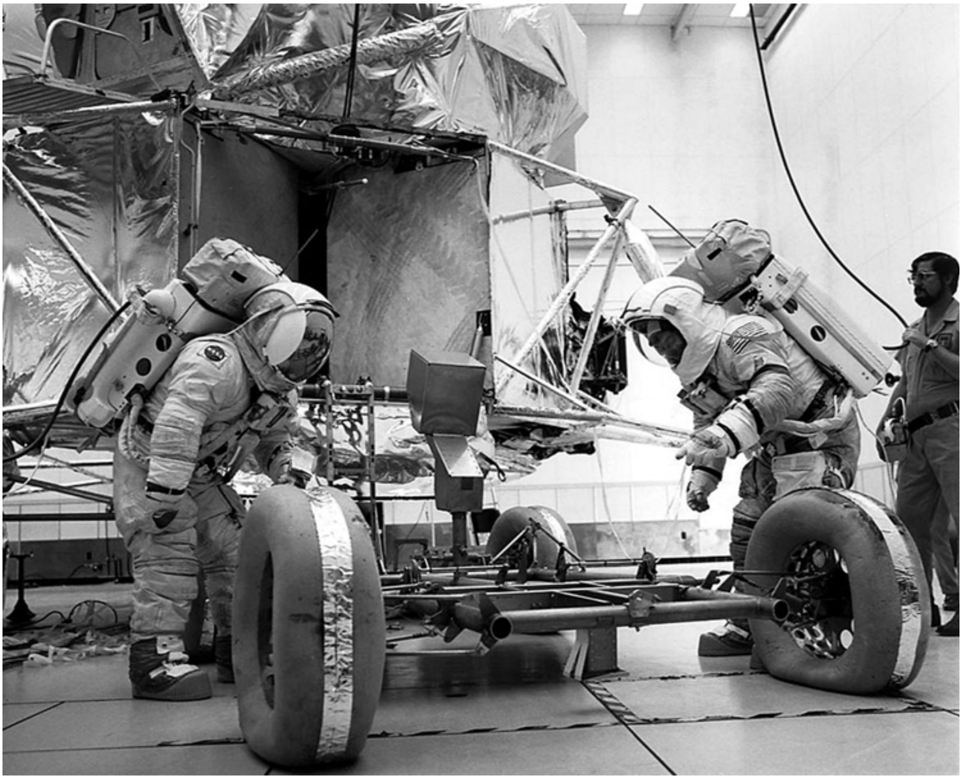
Crews also trained at KSC using the deployment trainer in the Flight Crew Training Building. The deployment trainer was fabricated from round aluminum tubing for the main chassis portions. The wheels used urethane foam over an aluminum form to give the wheel shape. The deployment trainer folded up like the actual LRV but the similarities ended there. It was of minimal construction and designed only to replicate the deployment sequence of the actual rover and attempt to duplicate movement as if in $\frac{1}{6}$ gravity. This trainer was deployed from a full-size mockup of the Lunar Module, which was also of minimal construction. Crews trained fully suited and their training included simulated problems of partial deployment and how to resolve those problems to complete deployment.

The 1-G trainer was also employed in the Flight Crew Training Building to go through the entire procedure of outfitting the LRV with all necessary equipment from the Lunar Module. Both the Commander and the Lunar Module Pilot worked together to outfit the 1-G trainer. This included installing the LCRU, High-Gain and Low-Gain Antennas, and the Color TV camera, and connecting the necessary cabling at the front of the trainer, as well as mounting the 16 mm Data Acquisition Camera, storing the 70 mm film canisters underneath the seats of the Crew Station, and installing the Aft Pallet Assembly with the Lunar Hand Tool Carrier and its related tools and equipment. The astronauts consulted their Cuff Check List on the left forearm of their suit as they went through this procedure.

TRAINING AT THE MANNED SPACECRAFT CENTER, HOUSTON, TEXAS

Astronaut training with respect to the Lunar Roving Vehicle employed some unique simulators. How could astronauts experience the performance characteristics of the Lunar Roving Vehicle operating in $\frac{1}{6}$ Earth's gravity? In September 1970, Donald "Deke" Slayton, Director of Flight Crew Operations, sent a memo to the Director of the Manned Spacecraft Center in Houston outlining his recommendations for using the centrifuge at the MSC with the 1-G Trainer, with modifications to the centrifuge to suspend the vehicle to simulate $\frac{1}{6}$ Earth's gravity.

"You requested that we evaluate the centrifuge for $\frac{1}{6}$ -G LRV simulation," Slayton wrote in the memo. "A preliminary evaluation indicates that the trainer can be installed on the centrifuge. Inasmuch as all the simulator hardware proposed for



J-mission crews practised using the Deployment Trainer in the Flight Crew Training Building at Kennedy Space Center, Florida. Capt. Eugene Cernan (right) and Dr. Harrison Schmitt are shown completing the deployment sequence on 8 June 1972 (Courtesy NASA)

the Building 5 TDS area (except the overhead trolley) would be required for the centrifuge, we would propose going ahead with the Building 5 simulator first, then transferring the simulator to the centrifuge. Why not do it only on the centrifuge? Because it is unrealistic to drive it on the centrifuge except in a constant speed turn. While we feel it is important to test the vehicle during the turns, we feel it is equally or even more important to see if the vehicle can be driven straight or along a slightly sinuous course.''

Suspending the trainer from the centrifuge operating at a given number of revolutions per minute would impose a certain amount of constant centrifugal force, Slayton pointed out to the Director. The centrifuge would have to be beefed up to support the vehicle and two astronauts. ''In summary,'' Slayton concluded, ''we would propose to test the vehicle at $\frac{1}{6}$ -G in Building 5 initially, then move to Building 29 for endurance-type tests dependent upon results from Building 5.''

This was done, and the trainer was eventually installed in the centrifuge for astronaut training. Jim Irwin and Dave Scott were the first two astronauts to use this

trainer for their upcoming Apollo 15 mission. Four special cylinders and cables suspended the trainer to give it the characteristics of driving at $\frac{1}{6}$ gravity; it was identified as the Pogo trainer. Irwin recalled this trainer to Eric Jones of the Apollo Lunar Surface Journal.

"You know, we had good one-sixth gravity simulations with that Pogo device in Houston," Irwin told Jones. "In fact, we could even suspend the little car from this device and remove five-sixths of its weight, so it essentially was at $\frac{1}{6}$ -G. And we could drive that 1-G version on a track. In fact, we used the centrifuge on it. The centrifuge was no longer used as a centrifuge, so this thing was suspended from the centrifuge track, and it would remove five-sixths of the weight, so we'd just drive it on a surface and have that similar bouncing sensation as we would on the Moon. So it was good driving simulations, and of course we also used that to practice walking. The Pogo device was like big suspenders attached to the spacesuit and they'd just remove five-sixths of your weight and you'd bounce along under that. And we could either use it underneath the centrifuge arm, which would follow us, or they even had it mounted on the back of a truck so we could go out and walk or run behind a truck to get the feel of operating on the Moon."

Dave Scott's recollection of this trainer was decidedly different from Irwin's. "As I recall it was not very effective, and I don't recall using it very much," Scott stated in

Jack Schmitt (left) and Gene Cernan drive Grover during a geologic field trip on the Pancake Range in south-central Nevada during September 1972. The appearance of the surrounding terrain was similar to what they would encounter at Taurus-Littrow. (NASA)

2005. “It was difficult to remove all of the 1-G effects. The LRV was so simple to drive and so responsive that actually very little training was necessary, especially since the full lunar terrain was not simulated”.

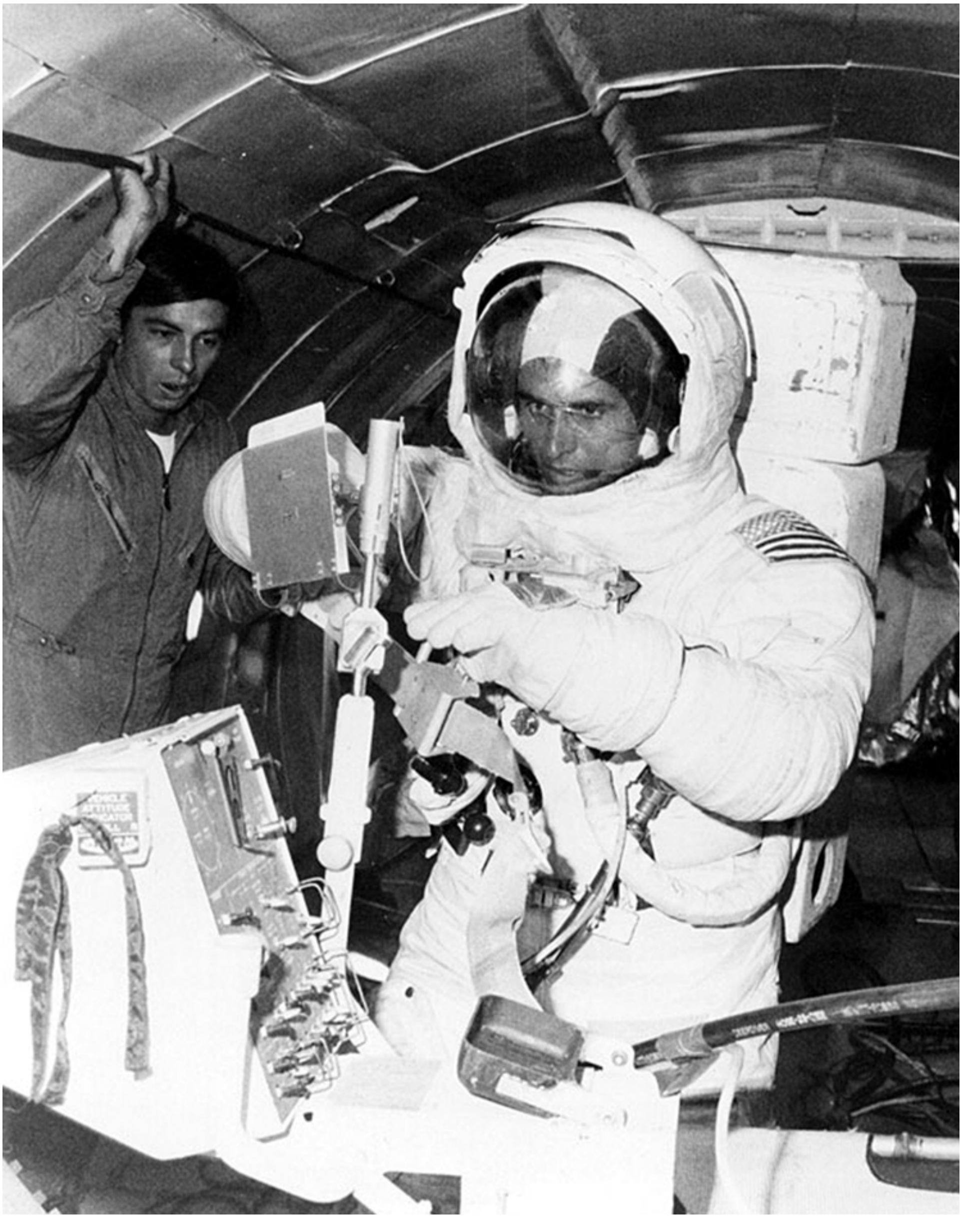
VISUAL SIMULATION TRAINING AT MARSHALL SPACE FLIGHT CENTER

During the late 1960s, a fixed-base visual simulator was developed by the Simulation Branch of the Computation Laboratory at the Marshall Space Flight Center to aid in the development of Lunar Roving Vehicle concepts prior to the eventual LRV design finally chosen. This simulator was designed to be used in conjunction with the Bendix Corporation and Boeing Company Lunar Roving Vehicle designs. The system was designed to present the driver with a reasonably accurate simulation of the lunar terrain. The basis of the simulator was a U.S. Air Force SMK-23. When the design direction for the Lunar Roving Vehicle moved away from the enclosed, pressurized vehicles to the open, unpressurized concepts, the simulator and software was modified to integrate the new human factors involved in the scaled-down Lunar Roving Vehicle.

“We had the full LRV and mission support teams, along with the support teams in Houston and Huntsville and the astronauts working on the 1-G trainer at KSC, involved in these joint integrated simulations,” recalled Ron Creel. “These ‘sims’ were a very important part of working through potential problems and solutions before the flights. To check out my real-time Forward Chassis thermal model prior to the Apollo 16 mission, I actually had my own integrated simulation performed in conjunction with the computer model, using playback of the Apollo 15 video tapes. This verified that the computer thermal model was ready to support the mission and perform analyses of potential alternate procedures, like turning off batteries and opening dust covers during EVAs.”

ZERO GRAVITY AND REDUCED GRAVITY TRAINING

To simulate the conditions of weightlessness and $\frac{1}{6}$ gravity on the Moon, NASA employed a special aircraft to fly parabolic flight paths to replicate these conditions for astronaut training. Most of these training flights originated from Patrick Air Force Base south of Kennedy Space Center, but training using this aircraft did take place at other locations. Formally known as the Reduced Gravity Program, it employed a KC-135 jet aircraft. The Crew Station Mockup (CSM) of the LRV was used for this training. The CSM included the major elements of the LRV from the toehold floor panels rearward; there was no forward chassis or mobility subsystem. This mockup was used on the aircraft for astronaut training in ingress and egress and securing the seatbelt, stowing and retrieving equipment from underneath the seats and assembling the all-important LRV Aft Pallet Assembly (APA) with its Lunar Hand Tool Carrier to the rear of the CSM, as the astronauts would have to do on the



Training for $\frac{1}{6}$ gravity on the Moon was accomplished aboard NASA's KC-135 aircraft, appropriately named the "Vomit Comet." Partial Lunar Rover sections were installed in the aircraft to practice seat ingress and egress and equipment installation. Pictured is Harrison Schmitt during one such training session. (NASA)

Moon. The Aft Pallet Assembly first had to be secured to the rear of the LRV CSM on its mounting points. The Lunar Hand Tool Carrier was then assembled to the APA. Due to the short 30-second duration of the $\frac{1}{6}$ gravity conditions before the aircraft had to pull out of its dive and climb back to altitude, many parabolas of the aircraft had to be flown to complete the scheduled amount of training. For that same reason, crews did not completely outfit the Lunar Hand Tool Carrier or perform other time-intensive tasks; this was performed on the ground in the Flight Crew Training Building.

"In retrospect," Harrison Schmitt remembered, "the flights were most useful for hardware development and probably less so for training due to the unrealistic times and conditions."

TRAINING – AN ASTRONAUT'S WAY OF LIFE

For the lunar landing missions of Apollo, years of actual training went into ensuring that a mission lasting less than two weeks went precisely according to plans. Training included not only the areas discussed in this chapter with relation to the LRV and lunar geology, it included virtually all aspects of the mission from the moment of liftoff to the moment of splashdown and recovery. It included abort during launch simulations; simulator training for transposition and docking of the Command Module with the Lunar Module, as well as rendezvous and docking of both spacecraft; and lunar landing simulations as well as abort during lunar descent, known as "fire in the hole", where the malfunctioning descent stage must be jettisoned and the ascent stage fired to return to a rendezvous with the Command Module. There were training exercises for almost every imaginable equipment failure or catastrophe that might take place from the moment of launch to the time of reentry. But there were some scenarios for which there could be no training. They could only be covered in mission procedures and rules.

The Apollo crews trained right up to the day before scheduled liftoff of their Saturn V. All this training paid off beyond measure with the success of Apollo 15, 16 and 17. Specifically, the geologic training the astronauts received ensured that the discoveries they made on the Moon would vastly expand our knowledge of our closest celestial body.

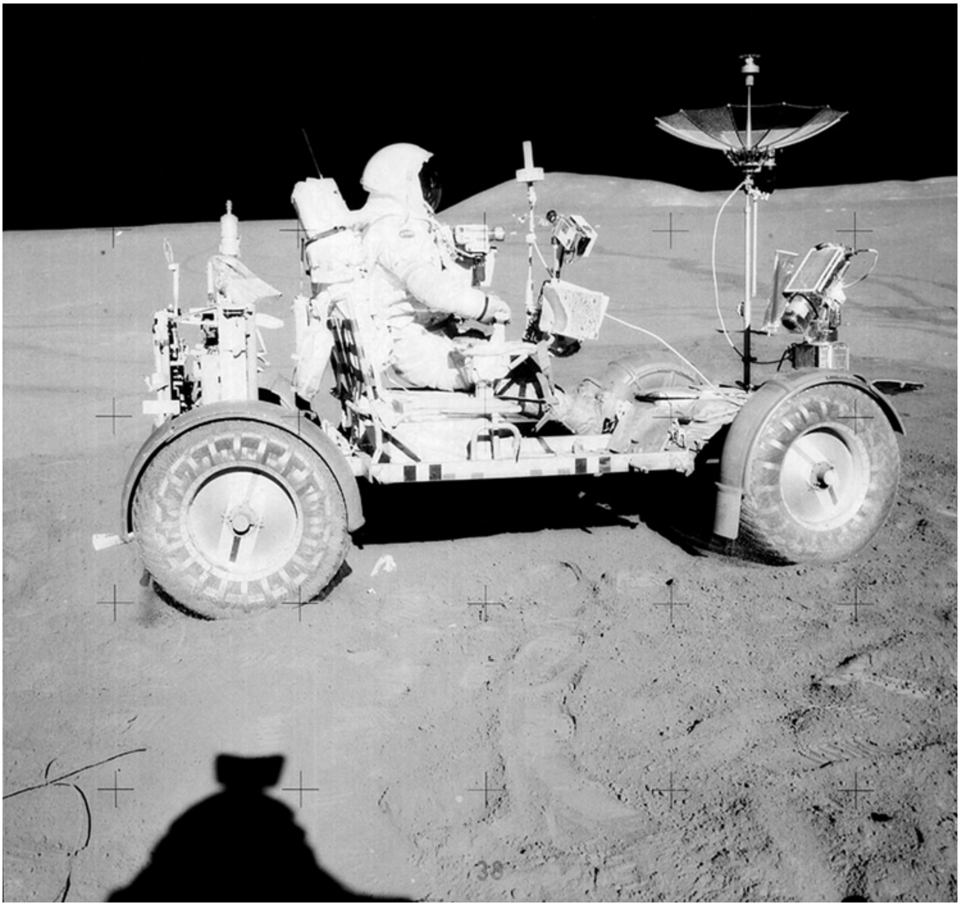
To the Hadley Plains

Arthur Scholz, Boeing's LRV project manager at Kennedy Space Center, stood at the edge of the Cape's famous Skid Strip. Measuring 45 m wide by more than 3,000 m long, the runway was built in the 1950s to permit landing of the U.S. Air Force Snark cruise missile. The Snark employed a simple three-point skid-type landing gear so the missile could be reused for program development. Today, 14 March 1971, the Skid Strip would receive a C-130 Hercules with a very special cargo: LRV-1. Scholz spotted the C-130 about the same time he heard the distinctive sound of the plane's four Allison turboprop engines. The plane made a smooth landing and soon came to a stop. The LRV had been shipped bolted to its shipping fixture; together they were offloaded onto a truck and taken to the Operations and Checkout Building. For the next six weeks, the rover would undergo an extensive series of inspections and performance checks. Acceptance took place at Boeing in Washington State; Checkout and Test would be conducted at KSC.

CHECKING OUT THE FIRST LRV

Once inside the O & C Building, the LRV was carefully inspected in its folded position. It was then removed from its shipping fixture using a specially designed sling hoist, placed on an inspection and test stand and securely bolted in place. The LRV was then unfolded and it underwent another series of inspections. The next week and a half was spent installing the battery simulators and checking out all of the vehicle's electrical systems, including the steering and drive mechanisms.

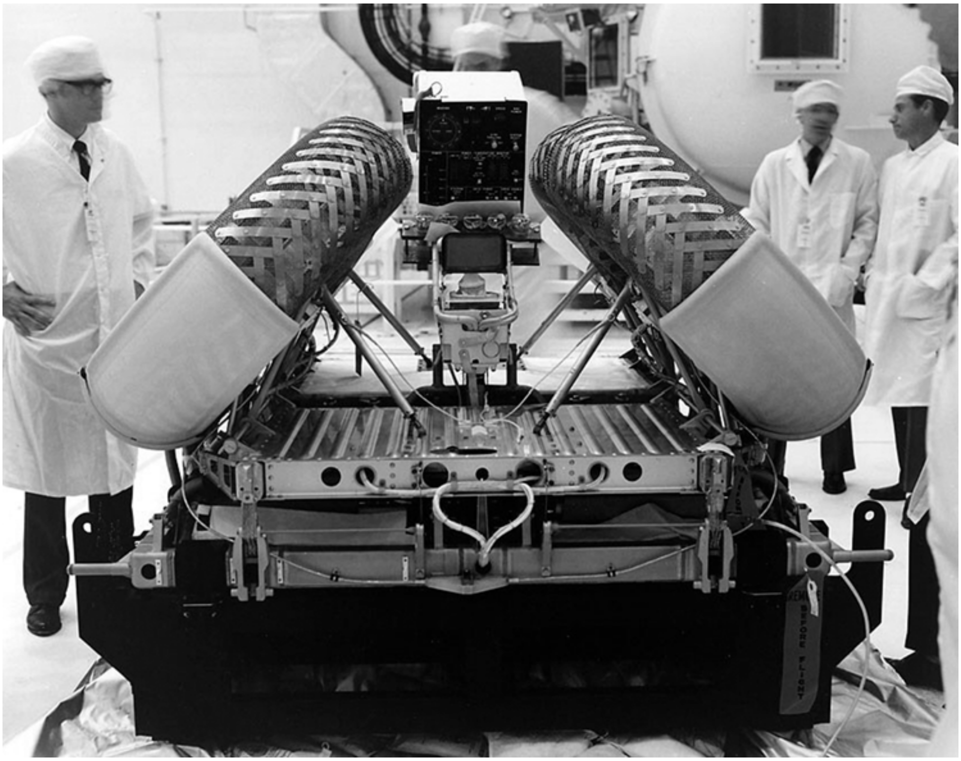
The first day for the initial Crew Fit and Function Test was 26 March. Both the prime crew (Commander David Scott and Lunar Module Pilot Jim Irwin) and the backup crew (Commander Richard Gordon and Lunar Module Pilot Harrison Schmitt) participated in these tests, which lasted for several weeks. There was an engineering fit check of crew equipment, during which the crews removed the antennas, TV camera, photographic equipment and other items from their stowage areas on the LM and loaded them into their proper location on the LRV. This phase revealed only balky equipment straps and the need for more readily accessible



The Lunar Roving Vehicle vastly expanded the exploration of the lunar surface, returned stunning live TV images to Earth and helped the astronauts to clarify the age and composition of the Moon. (NASA)

seatbelts. The astronauts insisted on the changes being made. Change orders were initiated but the paperwork took longer to get approved than it took to make the changes on the rover, requiring as it did an approval signoff from Boeing, MSFC, KSC and the Johnson Space Center in Houston.

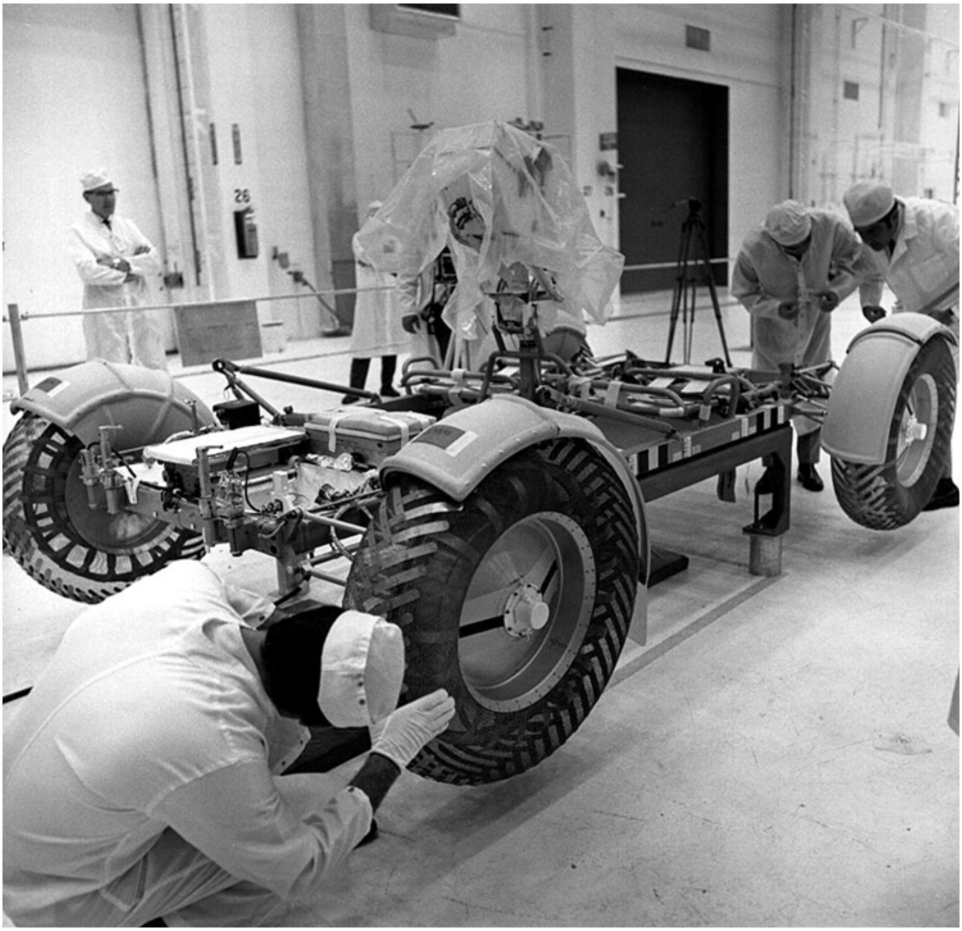
Then the unsuited crews participated in the installation of crew equipment, LRV wheel steering disengagement and thermal cover operation. This was done with the astronauts wearing only the EVA gloves, not the full suit. An important milestone was the Lunar Module/Lunar Roving Vehicle electromagnetic compatibility test, which checked the communication compatibility of the LM, EMU, LCRU, TV, and MSFN while operating all systems of the LRV. No interference was found to exist. A small silicone oil leak was discovered from the shock absorbers, but this was deemed acceptable for flight.



LRV-1 arrived at Kennedy Space Center on 14 March 1971. Here, it is shown still bolted to its shipping fixture prior to being placed on its inspection and test stand. The flags hanging from various parts of the LRV read "Remove Before Flight." (NASA/KSC)

Then it came time to test the loading of LRV No. 1 in Quadrant No. 1 of the Lunar Module *Falcon*. The LRV was completely folded and unbolted from its inspection and test stand. Using the special sling hoist, it was lifted, placed on and secured to the Handling and Installation Tool (HIT). The LRV and HIT were then lifted by the sling hoist, placed upon the Support Stand and then wheeled over to the Lunar Module. The Support Stand was adjusted to a predetermined height and locked in position. Then the LRV/HIT was pivoted into its precise location in Quadrant No. 1 of the LM where the LRV was secured and unbolted from the HIT, and the HIT returned to its original position. This was the first check for any interference between the LRV and the LM at KSC. None were found. The following day, the first deployment test took place, which was also successful.

On 21 April, the first of the mission simulation tests began with Scott and Irwin in their EVA suits. Representatives from Boeing, Grumman, RCA and many other companies involved with the LM or LRV were there, as well as those from KSC and MSFC. The mood was tense. Scott and Irwin entered the test area and walked around the LRV. Scott said, offhandedly, that the LRV was not configured



LRV-1, bolted to its inspection and test stand, undergoes detailed inspection inside the Operations and Checkout Building at Kennedy Space Center. Fender extensions are still in their stowed position. (NASA/KSC)

correctly. The team involved with the test was startled. Then Scott assured all those present that the crew could fix it and promptly produced a raccoon tail from the leg pocket of his suit, which he affixed to the right rear fender of the LRV, accompanied by the sounds of cheering, clapping and laughter. It broke the tension and the tests proceeded smoothly. The mission simulation tests were then repeated with Gordon and Schmitt. Another battery of communications tests also took place, which this time included the communications gear in the astronauts' suits. The simulated mission tests were completed with both the prime and backup crews and additional deployment tests followed, before the Acceptance, Checkout and Test team announced that LRV No. 1 was ready for flight. The batteries were removed, to be installed later on the pad, and the LRV stowed on *Falcon* on 25 April. Several

weeks later, the LM was secured inside the Spacecraft Lunar Module Adapter, the Command and Service Module joined to it, and the assembled spacecraft moved to the Vehicle Assembly Building, where it joined the Saturn V stack.

On 5 May, a press conference was held for the media, who were eager to see what the Lunar Rover was like. No one was more knowledgeable than David Scott and Jim Irwin, so they drove the 1-G trainer out to the press site near the LRV training area. The astronauts spoke to the correspondents about the capabilities of the LRV, what the crew planned to accomplish with it, answered their questions, and even let some of the press members drive it, with a Boeing engineer next to them. The press covering the launch was truly enthusiastic about the LRV and it proved the focus of their articles up to the day of launch.

THE LANDING SITE, MISSION RULES, AND LUNAR SCIENCE

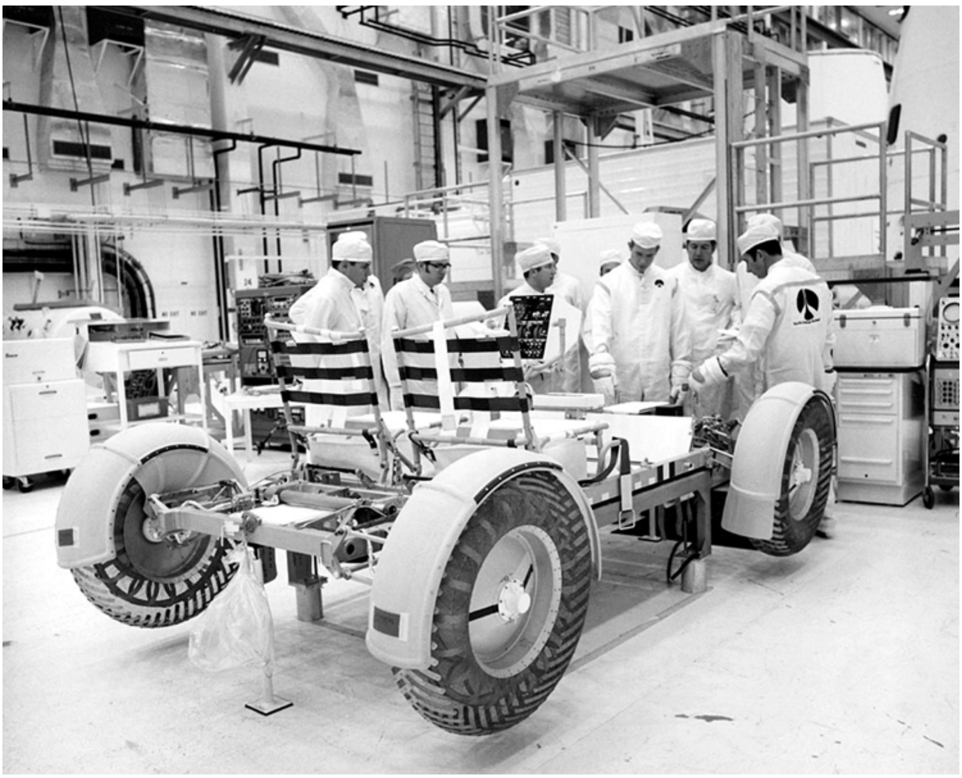
Deke Slayton had announced the prime and backup crews for Apollo 15 on 26 March 1970, two weeks before the launch of Apollo 14. For the prime crew, he selected astronauts with previous backup crew or prime crew experience. David R. Scott was selected as mission Commander, Jim Irwin as Lunar Module Pilot, and Alfred Worden as Command Module Pilot. For the backup crew he named Richard F. Gordon as Commander, Jack Schmitt as Lunar Module Pilot and Vance D. Brand as Command Module Pilot. Later that year, the Apollo Site Selection Board had some tough decisions to make. The plunging NASA budget put pressure on the future missions planned, and there were necessary casualties. Apollo 15 and 19 were cancelled in September 1970 and the remaining missions renumbered. Apollo 18 was also in jeopardy. The Manned Spacecraft Center suggested to the Apollo Site Selection Board that the Hadley-Apennine region, located on the southeast edge of the Mare Imbrium (Sea of Rains) and named for the British scientist and mathematician John Hadley (1682-1744), was a rich geologic choice, but there was keen interest in the Marius Hills as a possible site for the new Apollo 15 mission. As happened with several other chosen sites, there were champions for each option and the Board could not make an unarguable decision. Col. David Scott, who had only recently been selected as Commander for Apollo 15, stated that he preferred Hadley, but felt confident that he could land at either site. This broke the impasse, and the ASSB recommended the Hadley region with its distinctive rille and towering Apennine Mountains for a landing sometime between July and September 1971.

Eugene Shoemaker of the USGS had written the proposals submitted to NASA for the lunar surface sampling and photography tasks for Apollo 11, 12 and 13, as principal investigator. Shoemaker asked Gordon Swann to be a co-investigator for these missions and it was this experience that eventually led to his responsibilities for Apollo 14 and 15. At the time Apollo 11 through 13 flew, Shoemaker had left the USGS and taken a professorship at Caltech. He left the operation of these missions, in a lunar geology sense, to Swann.

"He told me I was to run some things for him," Swann recalled. "We had had a long thing going with trying to set up where we could have a presence in the Mission

Control Center and some input during the mission, which we were successful in doing. I was highly involved with that part. Gene just kind of dropped it on me, saying, 'You put together the actual working crew for the experiments that will be in the control center during the missions,' so I did. Then NASA put out an RFP (Request for Proposals) for the rest of the missions. Originally, 14 and 15 were going to be walking missions and 16, 17 and 18 would be missions with the rover. So I proposed for 14 and 15 and Bill proposed for the rover missions. Well, NASA cancelled 18 and decided to fly the rover on 15. Should that be Bill's or should that be mine? Bill and I talked it over for a few minutes and Bill said, 'Why don't we just divide them? You take 14 and 15, and I'll take 16 and 17.' So that's what we did.

"The proposal for 15 was primarily to do the field geology part," Swann continued, "going out and taking photographs, the sampling, the descriptions and doing our best to decipher the geologic history of the Moon. We had a lot of responsibility to see that samples were taken that would satisfy however many investigators there were for them. We developed, pretty much at NASA's insistence –



David R. Scott (to the right of the Control and Display Console) and James B. Irwin (back to camera) inspect LRV-1. Both astronauts are wearing EVA gloves to get the feel of handling various parts of the rover. Wheel construction is clearly visible in this photo. (NASA/KSC)

that is, the Manned Spacecraft Center's insistence – these traverses. The field geology bunch and some NASA people, including Jack Sevier particularly and the astronauts, worked out these pre-planned traverses. NASA looked at everything in an engineering sense against a timeline – how long it would take to perform a certain task. Field geologists don't work that way, so we had to try to make the best guess that they could do these tasks and get the information necessary in 'X' number of minutes and how long it would take to get to the next place. That's where Jack Sevier of the MSC really came in and got the scientists working together on this stuff.

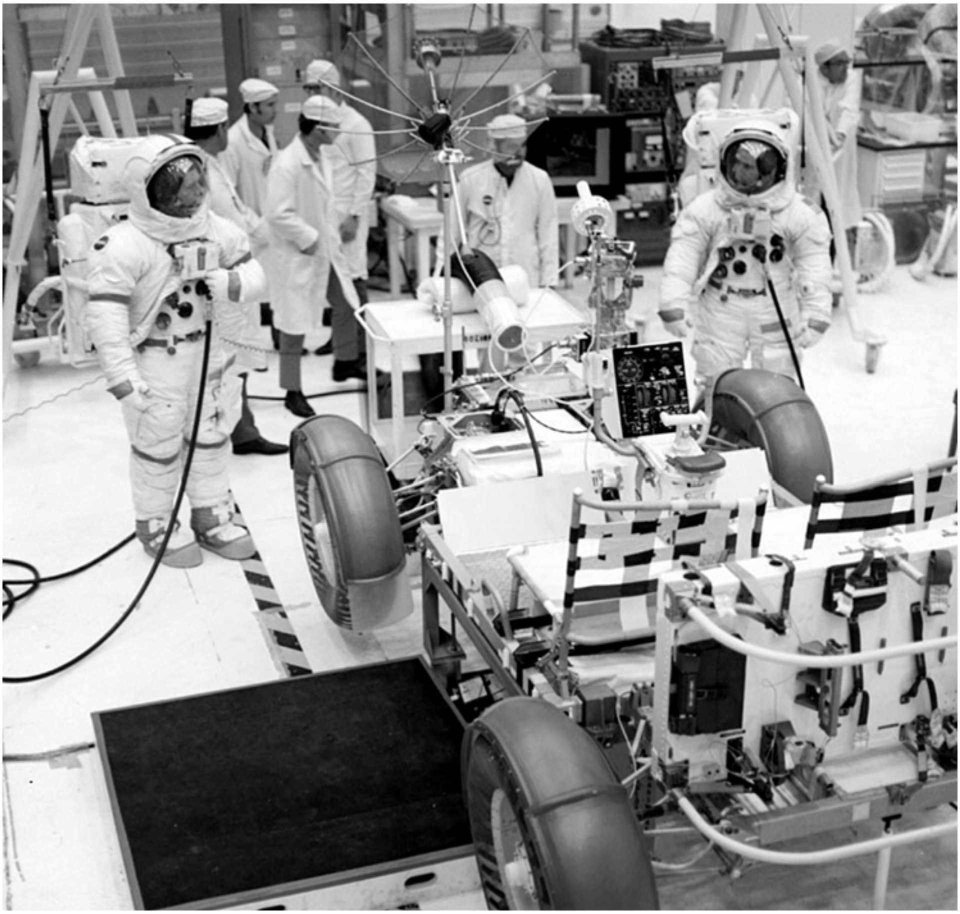
"On 15," Swann stated, "the co-investigators included Bill Muehlberger from the University of Texas at Austin, Jim Head from BellComm, and Lee Silver from Caltech. From the USGS there was Jerry Schaber, who was also involved in traverse planning and crew briefing, Tim Hart, Robert Sutton, George Ulrich and Ed Wolfe. We also had two or three other people we called team members, who were non-geologists that supported the preparation for and during the mission. These included Ray Batson of the USGS who was responsible for photogrammetry and the inventor of gnomon, and Johnny Nutall, who took care of all the electronics of the field tests, and had a job in the Mission Control Center."

Meticulous planning

All geologic training would now be focused around the Hadley region. Apollo 15 would be the first of the extended "J" missions, which included the Lunar Rover. Mission planners would spend the next sixteen months planning practically every minute of every hour, from the moment of liftoff to the moment of splashdown.

The thoroughness of mission planning and establishing mission rules were just two of the reasons for the success of project Apollo. There were, in fact, a countless number of things that could go wrong at any time in the mission. The mission team tried to account for most of these and to have contingency plans available. Apollo 13 was an example of such a failure (the explosion of the No. 2 cryogenic oxygen tank ruptured the No. 1 cryogenic oxygen tank in the Service Module) and that did indeed mean a very bad day for the crew. Even here, the resourcefulness of the mission team produced backup procedures and emergency measures that preserved the crew and the spacecraft and made Apollo 13 a triumphant success instead of a tragic failure. With the Lunar Roving Vehicle and the extended nature of Apollo 15, the mission rules were even longer and more involved. There were many "firsts" for Apollo 15, and a great deal to be accomplished. The purpose of mission rules is to avoid the temptation of deviating from them even when the mission is going well.

"We developed a lot of mission rules for the rover," Dave Scott said in the interview with this author. "Part of the pre-flight exercise – our activities pre-flight – was not only developing these procedures to say who gets on first or what emergency procedures do we have in case this fails or that fails, but also writing the mission rules. We would all sit down with the flight director and go through all the "what ifs" with the rover so that if we did have a problem, we'd have a mission rule. In that philosophy, you pretty much exclude double failures. As an example, you exclude the failure of the rover *and* a failure of one of the astronauts' backpacks (PLSS –



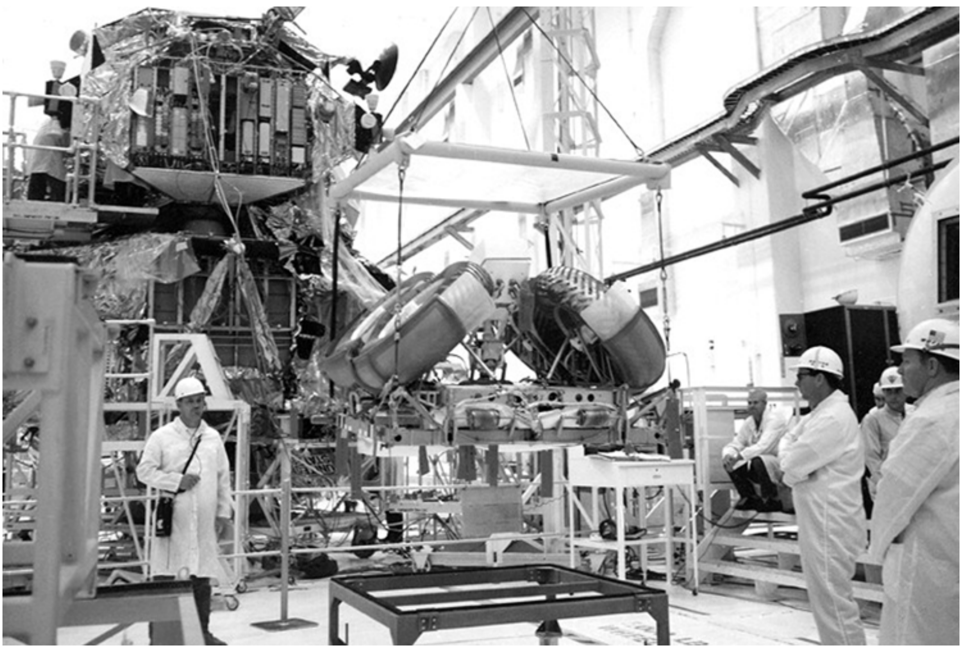
Scott (left) and Irwin prepare for one of the Crew Fit and Function Tests with LRV-1. With the LRV raised up off the floor while on its inspection and test stand, platforms were placed on both sides of the vehicle to permit astronaut ingress and egress. (NASA/KSC)

Personal Life Support System) because if you have that kind of failure, one guy doesn't get back. You can walk back with two backpacks if the rover fails, and that's how you define the distance you can go from the LM, which is time-dependent on your oxygen supply.

"If you get to the limit of your oxygen supply," Scott continued, "Mission Control would start you back so that if the rover failed at any point, you could walk back. At the same time, the other factor in that is if one of the backpacks fails, you could have the buddy's list and you would tie the cooling hose together. You would have the OPS for oxygen, and you would drive back. That was another limit Mission Control had to watch in terms of how far away we were. But, if you had a rover failure and a backpack failure, you had a bad day. That was a double failure, and

you get to the point where you can't cover everything. That was the beauty of the exercise of developing mission rules. It allows you to go through all those "what ifs" with all the smart guys in the room. You would have twelve to fifteen guys, each of whom would be an expert in some part of the system, and you would spend several hours going through the "what ifs." Everybody makes their input, you write down the mission rules and then you are pretty well prepared."

Three primary EVAs were planned for Apollo 15 at the Hadley-Apennine region of the Moon. During the first EVA, Scott and Irwin would drive the LRV over to Hadley Rille and drive along the edge until they got to Station 1 near Elbow Crater. Their next stop would take them to Station 2 close to the rim of St. George Crater at the base of Hadley Delta. Then they would travel to Station 3, where they would continue to take samples and photographs. Next, they would drive back to the LM *Falcon* and deploy the various surface experiment packages. The following day, EVA-2 would take them past a crater region known as the South Cluster and on to the base of the Apennine Front. From there they would travel to Front Crater, and loop back following a parallel traverse, again passing the South Cluster as they made for Index Crater and finally back to the LM. On their third and last day on the Moon, EVA-3 would take them to Hadley Rille, where they would make three station stops along The Terrace, as it was called. Then they would make the traverse up to the Chain Crater cluster, on to Eagle Crest Crater and the North Complex that



LRV-1 is lifted from its inspection and test stand by the sling hoist, for placement on the Handling and Installation Tool (HIT) visible at left. (NASA/KSC)

included the massive 750-meter Crater, then across the Hadley Plains back to the LM.

The Apollo 15 Press Kit handed out to eager reporters on 15 July was the largest ever presented to the media – over 160 pages long. It stated that the mission would "Double the time and extend tenfold the range of lunar surface exploration as compared with earlier missions." Among the obvious advantages of having the LRV was the access to more tools, greater sample carrying capacity and much more geologic exploration capability. The astronauts' improved PLSS increased the total EVA duration from eighteen to forty hours, which meant that the astronauts could remain outside on a single EVA for almost twice as long as on previous missions. The LM was modified with larger oxygen and water tanks (and a more powerful descent engine) to accommodate nearly doubling the stay on the Moon from thirty-seven to sixty-seven hours. The press kit's description of the landing site in particular is worth quoting at length:

> "The Apollo 15 landing site is located at 26 degrees 4 minutes 54 seconds North latitude by 3 degrees 39 minutes 30 seconds East longitude at the foot of the Apennine mountain range. The Apennines rise up to more than 15,000 feet along the southeastern edge of the Mare Imbrium (Sea of Rains).
>
> "The Apennine escarpment – the highest on the Moon – is higher above the flatlands than the east face of the Sierra Nevadas in California and the Himalayan front rising above the plains of India and Nepal. The landing site has been selected to allow astronauts Scott and Irwin to drive from the LM to the Apennine front during two of the EVAs.
>
> "A meandering canyon, Rima Hadley (Hadley Rille), approaches the Apennine front near the landing site and the combination of lurain (lunar terrain) provides an opportunity for the crew to explore and sample a mare basin, a mountain front and a lunar rille in a single mission.
>
> "Hadley Rille is a V-shaped gorge paralleling the Apennines along the eastern edge of Mare Imbrium. The Rille meanders down from an elongated depression in the mountains and across the Palus Putredenis (Swamp of Decay), merging with a second rille about 62 miles (100 kilometers) to the north. Hadley Rille averages about a kilometer-and-a-half in width and about 1,300 feet (400 meters) in depth throughout most of its length."

The press kit devoted twenty-four pages to the LRV, including its telecommunications equipment. Indeed, the Hadley-Apennine landing site would prove to be a very wise choice from a lunar geology standpoint, and the Lunar Roving Vehicle would permit the astronauts the maximum opportunity to explore its many secrets. The LRV and what it would allow Scott and Irwin to do on the Moon was responsible for sparking renewed interest in the last Apollo missions. Mission planners were banking on the LRV performing as advertised and that the RCA TV camera, which could be remotely controlled from Houston, would beam back images that would justify to incredulous Americans that it was worth all the expense.

"Hadley Rille had to be the most interesting geologically," Irwin wrote, "because of the rocks themselves and the dramatic site, tucked in among those high

Once secured to the HIT, LRV-1 was pivoted into its location on the Lunar Module *Falcon*. Fit checks were initially performed to ensure that there were no interferences between the LRV and the Lunar Module. (NASA/KSC)

mountains. We strongly supported the selection of the Rille as a landing site for 15, and we were delighted when this choice was made''

LRV CLOSEOUT

During the last weeks prior to launch, the Mobile Service Structure (MSS) was moved into position adjacent to the Saturn V using the Crawler Transporter. The MSS was an invaluable component of the Apollo launch facilities and permitted

access to virtually every portion of the launch vehicle. Three days prior to launch, during the Lunar Module closeout procedures, the LRV underwent a procedure of its own. From the work platform, an access panel in the Spacecraft Lunar Module Adapter (SLA) which housed the Lunar Module was removed. Once technicians were inside, the floor panels of the LRV were removed using a special removal tool. The batteries were delivered to the work platform by two technicians using the battery installation tool. The technicians wore slings to secure this tool. Once the batteries were installed, a battery monitor cable was run from the batteries to the battery monitor box mounted at level 260 of the Launch Umbilical Tower (LUT). The batteries were then load tested using the monitor box. Interface cables were then attached between the monitor box and the ACE peripheral equipment at ground level. The batteries were charged and monitored from launch control until eighteen hours before launch. At that time, technicians disconnected the monitor cables and removed the monitor box from the LUT. Flight configuration coverings were installed in the LRV, its floor panels installed and secured with bolts, and aluminum tape applied in designated areas of the floor panels.

Once closeout of the Lunar Module was complete, the panel was secured to the tapered section housing it and the Lunar Module and the LRV were officially closed out. There was no provision for monitoring the batteries (due to weight constraints) until the Lunar Rover was finally deployed on the Moon's surface nearly ten days hence. No one could know if they were healthy or had suffered some mishap during the launch, the trip to the Moon or the landing. For many involved with the "J" missions, that was cause for some nail-biting. The manufacturer of the batteries, Eagle Picher, had every confidence the LRV's batteries would perform as promised, but no one would know for sure until the vehicle was deployed on the Moon and powered up.

LAUNCH DAY – 26 JULY 1971

"Okay, guys, this is it," Deke Slayton announced to Scott, Irwin and Worden as he woke his crew at 4:19 a.m. on the third floor of the crew quarters at Kennedy Space Center. They each put on bathrobes and walked down the hall to the medical examination room for a quick pre-launch physical. Dr. Clarence Jernigan checked each astronaut and gave them a clean bill of health. Scott and Irwin went back to their quarters to get dressed for breakfast, but Worden chose to have the traditional pre-launch breakfast of steak and eggs in his robe. All three men appeared to be relaxed, but were quieter than usual, lost in their thoughts of the imminent launch. The backup crew was there having breakfast also, but there was little conversation. Breakfast over, the crew went down to the suit room. They undressed, received a second examination by Dr. Jernigan, had bio-medical sensors applied to their bodies, and then began the methodical process of suiting up with the help of technicians. They were now breathing pure oxygen to purge all traces of nitrogen from their bloodstreams prior to launch, which was still several hours away. After a period of rest on recliners, Slayton received the call from the launch pad that the mighty

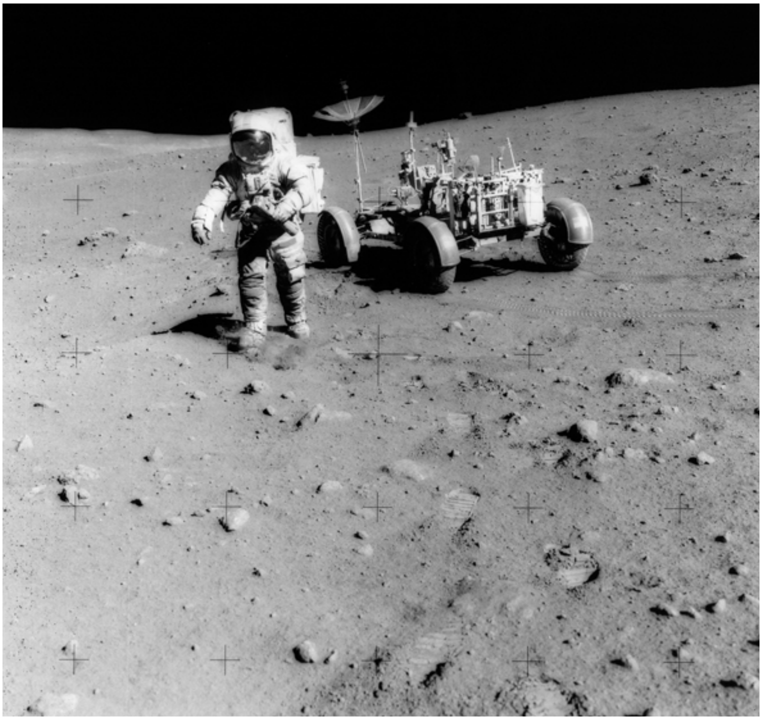
Saturn V was finally ready for the crew. With their portable air conditioning units in hand, the crew of Apollo 15 left the building at 6:30 a.m., waved to the press photographers and well-wishers as they got into the crew transport van with Slayton, and rode out to Pad 39B.

The crew took the elevator of the Launch Umbilical Tower (LUT) to the top and walked one by one across the last swing arm to the closeout room that surrounded the Command Module *Endeavor*. Waiting for them was Guenther Wendt, the always-smiling pad leader who, with his crew, assisted the astronauts into the capsule, made the necessary air conditioning and communications connections, and securely strapped them into their couches. He wished them a safe flight, and the heavy capsule door was closed and locked. A panel that covered the capsule door as part of the Boost Protective Cover was secured in place and Wendt and his crew left the closeout room, took the elevator down to ground level and left the pad. The countdown of Apollo 15 proceeded smoothly with no delays right to the moment the launch window opened at 9:34 a.m.

At T minus nine seconds, the ignition sequence started. The turbopumps of the five F-1 engines started simultaneously, injecting the liquid oxygen and RP-1 into the combustion chamber and igniting the volatile mixture. The engines roared to life, quickly building up to more than 1.5 million pounds of thrust each. It took several seconds for the thundering cacophony to reach the press and spectators at the viewing area near the VAB. Like some erupting volcano, huge clouds of smoke billowed from beneath the launch platform and shot into the sky. The swing arms pulled away from the shuddering rocket that was now generating 7.7 million pounds of thrust. The four hold-down arms restraining the Saturn suddenly released, the astronauts heard the voice of Mission Control bark, ''Liftoff!'' and the largest rocket in the world quickly accelerated, clearing the Launch Umbilical Tower in a matter of seconds. Watching from the launch control room were Gen. Samuel Phillips, director of the Apollo program within the Manned Spacecraft Office, Dr. Wernher von Braun, NASA Administrator Dr. James Fletcher and NASA Deputy Administrator Dr. George M. Low. Von Braun was confident that he would see the Lunar Rover traveling across the Hadley Plains several days hence.

At 57 seconds, the Saturn was already at 25,000 feet. At 2 minutes 30 seconds, the event some astronauts call the ''train wreck'' but which is officially known as staging, took place. The center engine shut down first, but the moment the remaining four F-1 engines shut down, the three astronauts were thrown against their restraining harnesses. The first stage dropped away, followed by the inter-stage ring. The five J-2 engines of the second stage then ignited, thrusting the astronauts back into their couches. At 3 minutes and 21 seconds, the Launch Escape System, no longer needed in the event of an abort, was jettisoned, taking with it the Boost Protective Cover.

''After the cover blew we were going straight up, and we saw blue sky that got blacker and blacker,'' Jim Irwin wrote in his autobiography *To Rule the Night*. ''Once into Earth orbit, we could see blue skies below and black skies above. Right in the middle of my window was a full Moon. Seeing the full Moon was a terrific omen. I knew we were going to have a great mission.''



The Apollo 15 landing site did not feature many large boulders as was originally suspected, but the area was heavily populated with blocks, as shown here during EVA-3. These conditions gave the LRV's suspension and wheels a real workout. Dave Scott is seen holding his Hasselblad camera with 500mm lens. (NASA)

The S-II stage continued to burn smoothly until 9 minutes and 16 seconds when the engines shut down and staging took place once more. The crew of Apollo 15 was now 1,800 km downrange at 175 km altitude and traveling at more than 7,000 meters per second. The single J-2 of the S-IVB fired to place them in their proper orbit, and shut down at 11 minutes and 34 seconds.

RENDEZVOUS WITH THE MOON

After two orbits, the crew received the "go" for Trans-Lunar Injection (TLI). Precisely on time, the S-IVB single J-2 engine restarted and burned for six minutes to build to escape velocity. A mere 27 minutes after the TLI burn, the Command and Service Module separated from the S-IVB stage, turned 180 degrees and Al Worden inched *Endeavor* toward the stowed Lunar Module. Worden achieved hard dock with the LM and successfully extracted it from the upper stage. After the spacecraft were a safe distance away, the S-IVB fired its engine one last time and was sent on a trajectory to impact on the Moon. The next three days would pass quickly for the

crew as they checked out the Lunar Module *Falcon* and went through their extensive check list in preparation for Lunar Orbit Insertion (LOI). As the spacecraft went behind the Moon, the Service Propulsion Engine was fired to put the crew into their initial lunar orbit. The Manned Spacecraft Center in Houston would not know if the burn was successful until the spacecraft came round from behind the Moon and transmitted the good news back to Earth.

"All of a sudden we came from darkness into daylight," Irwin wrote. "You are at the Moon! It hits you just like that. It is the most beautiful sight to look out and see this tremendously large planet. You'd never guess that the Moon would be that big, even though you have seen all the pictures. But here you are seeing it with your own eyes for the first time. It is staggering. You can barely see the curvature of it. You are coming around and moving not too fast, at medium speed, and you cross the terminator, which is that line between darkness and light. Coming from the back side, the first large feature that we saw was Tsiolkovsky Crater, with its high central peak of light-colored material surrounded by a dark sea. The crater must have been fifty miles in diameter and probably as deep as the Grand Canyon."

Scott, Irwin and Worden all voiced their impressions of the Moon as they traversed over its surface below, describing what they saw in detail to the countless eager ears back on Earth. They circularized the orbit of their spacecraft and lowered it in preparation for *Falcon's* descent the following day. At 100 hours, 39 minutes Ground Elapsed Time (GET), Scott and Irwin separated *Falcon* from *Endeavor* and began their descent to their landing site. As the LM passed the 2,700 m level, Scott and Irwin could see the 3,350 m summit of Hadley Delta up and to their left, and the 4,270 m peak of Mount Hadley up and to their right. It wasn't until the LM performed its programmed pitch-over that the two astronauts could finally see the serpentine Hadley Rille dead ahead. Scott brought *Falcon* in smoothly as Irwin read off the descent and speed figures. At 30 m the descent engine began kicking up lunar dust. Irwin waited for the contact light to illuminate when the first landing gear probe touched the lunar surface.

"The light came on," Irwin wrote. "I called 'Contact!' Dave immediately pressed the button to shut the engine – and then we fell. We hit. We hit hard. I said, "BAM!" but it was reported in some of the press accounts as "damn." It was the hardest landing I had ever been in. We just froze in position as we waited for the ground to look at all our systems. They had to tell us whether we had a STAY condition. As soon as we got the STAY, we started powering down. Evidently, we had landed right on the rim of a small crater. Dave and I pounded each other on the shoulder, feeling real relief and gratitude. We had made it."

Dave Scott's impression of the landing was decidedly different from Jim Irwin's. The Commander had to hit the engine stop button the moment the contact light came on because he was concerned that the extended descent engine bell might rupture if the engine was still firing when the LM landed on the lunar surface.

"I think the difference was," Scott stated during this author's interview, "that he was focused on keeping me updated with how we were doing and not with the fact we were getting close to the surface. When we landed, we put a rear footpad in a crater because I couldn't see anything because of the dust. It was sort of a double hit. You

hit on three pads and one fell into the crater. I guess Jim just wasn't expecting it."

With this welcome news from Houston for a "Stay", the geologic and scientific teams looked forward to the discoveries that awaited. Looking out of the windows of the LM *Falcon*, Scott had some encouraging words for the excited science teams back on Earth.

"And Houston, the Hadley Base here," Scott announced. "Tell those geologists in the Backroom to get ready because we've really got something for them."

THE STANDUP EVA

Scott and Irwin then began going through their check list in preparation for the first – and last – EVA of its kind during the Apollo missions. The two astronauts would don their helmets and gloves, pressurize their suits, and then Scott would open the overhead hatch and remove the docking drogue assembly to perform a Standup EVA (SEVA). This was essentially a site survey to see whether the area was strewn with boulders or was clear enough to employ the Lunar Roving Vehicle.

"One of the reasons for the standup EVA since we were working with the rover," Scott said during the interview, "was that we had been told by the radar people that there were boulders – lots of boulders – at Hadley. Our photos of the area had a resolution only down to 20 meters, so in the photo, you couldn't really tell. So, one reason for the standup EVA was to check the trafficability of the area to see if we could drive the rover. If you are looking at two-, three- or four-foot boulders around, the rover isn't going to be much use. Fortunately, there were none."

Another reason for the SEVA was to take photographs of the entire surrounding area of the Hadley landing site. Scott was encouraged by what he saw. While there were many small craters, the plain for as far as he could see was free of boulders of any size. As he took photographs with the Hasselblad camera and described the lunar terrain, he spoke in terms of a trained geologist. As he did so, he also dispelled preconceived notions of the Hadley region of the Moon. As previous Apollo missions had proved, and Apollo 15 was already proving, there was no substitute for manned exploration. He described Hadley Delta, he could see the Northern Complex of craters and the inner walls of Pluton Crater and he identified Icarus and Chain Craters. Scott could not see the edge of Hadley Rille but he could see its far side. After finishing the photography and his description of the region for a rapt audience back in Houston, Scott closed out the SEVA by replacing the docking drogue and closing the hatch. They re-pressurized the LM, removed and stowed their suits and broke out their food for their first meal on the Moon. That night the astronauts slept well, eager for the next day's activities.

EVA-1: DEPLOYING THE ROVER AND THE FIRST TRAVERSE

The two astronauts got an early wakeup call from Houston at 115.5 hours into the mission. They checked out a minor pressure drop in the descent stage oxygen tank,

On the right side of the Control and Display Console was affixed a plaque identifying the men who brought the LRV to the Moon. It reads: "Man's First Wheels on the Moon. Delivered by Falcon. July 20, 1971", with the signatures and names of David R. Scott, Alfred P. Worden, and James B. Irwin (NASA)

and went through their check list for the morning in preparation for their first EVA. They also had breakfast. It took over four hours to complete all the preparations but once their suits were on, they depressurized the cabin, opened the hatch, and Scott made his way out to the Lunar Module's "porch." He activated the Lunar Surface TV camera and CapCom Dr. Joseph P. Allen reported getting a good picture. The audience for the images being beamed back to Earth was the largest since Apollo 11. Also watching with the greatest of interest was Saverio Morea and his team in Huntsville, the entire Boeing LRV team and their subcontractors, and Dr. Wernher von Braun, who was witnessing yet another piece of the Apollo lunar exploration puzzle being put into place. The LRV was really the focus of attention. The entire mission, in fact, hinged upon it. It had to perform or Scott and Irwin would have to resort to the walking traverse plan. Scott pulled a D-handle to retract the three pins holding the LRV to its attachment points, in preparation for its deployment. A spring-loaded push-off rod moved the folded rover away from the LM by about 12 cm until it was stopped by two deployment cables. Scott descended the ladder to the Lunar Module's footpad and then stepped onto the lunar surface.

"Okay, Houston," Scott radioed to Mission Control, "As I stand out here in the wonders of the unknown at Hadley, I sort of realize there's a fundamental truth to our nature. Man *must* explore. And this is exploration at its greatest. Well, I see why we're in a tilt ... There's so much hummocky ground around here [and] we're on a slope of probably ten degrees. And the left-rear foot pad is probably about two feet lower than the right-rear foot pad. And the left-front's a little low too. But the LM looks like it's in good shape. The Rover's in good shape."

Scott's last comment on the condition of the LRV produced a collective sigh from the rover team on Earth after the *Falcon's* hard landing, but there were still concerns about what effect the landing may have had on the condition of the rover's many systems. No one would know the condition of the batteries until the vehicle was unfolded, its chassis locked in position and then powered up. Irwin soon joined his colleague on the surface of the Moon. In order to view the rover's deployment, Scott set up the Ground-Commanded Television Assembly (GCTA) tripod roughly ten meters away from the LM, then moved the TV camera from its place in the Stowage Mount Assembly of the MESA to the tripod. Scott mentioned to Houston that pointing the TV camera toward the LM would have it looking almost directly into the Sun, so he moved the tripod and camera into *Falcon's* shadow and the problem was solved.

Both astronauts then began deployment procedures, but before doing so, Scott discovered one of the deployment walking hinges was unlatched. Irwin noticed the other was also unlatched and in this condition, the rover would not properly deploy. So the astronauts reset the walking hinges, something they had practiced many times on Earth. Scott and Irwin then walked several meters away from the LM and began pulling on their respective deployment tapes. The rover began its descent. Just past 45 degrees, the rover's rear chassis and wheels deployed, somewhat startling the astronauts. Scott advocated caution as they continued slowly pulling on the tapes but soon the rear wheels were on the surface. Shortly thereafter the front chassis and wheels deployed. Because the LM was at an angle on the lunar surface, the rover was not ideally positioned in this phase of deployment, and Irwin had to pull more than Scott. The two astronauts had to lift the rover and pull it away from the LM to release it from the supporting saddle, but on the Moon, because it weighed a mere $\frac{1}{6}$ of its weight on Earth, both astronauts found it easy to move.

They then continued pulling on the deployment tapes and the LRV settled completely on the surface. Scott and Irwin checked that the chassis locking pins were properly seated and that the instrument and control console was also locked in position. The two men then picked up the rover and turned the front end away from the LM so it would be in position to drive away. Then the toe holds were inserted, the seatbacks and foot rests erected, fender extensions moved and locked into position, seatbelts released, and the docking pins and latches removed from the rover.

Learning to drive on the Moon

Scott then got into his seat in preparation for powering up the rover. He read off the critical amps, voltages and temperatures to Houston, reporting no amps or voltage

on battery No. 2. This turned out to be an indicator problem and the rover did indeed have both batteries functioning. Irwin took the 16 mm film camera in hand and told Scott to let him know when he was ready to drive off so he could film the rover underway. Joe Allen admonished Scott to "Buckle up for safety." And then Scott moved the hand controller forward of its detent, or neutral position.

"Okay," Scott said to Houston, "out of detent. We're moving"

"Extraordinary," Allen remarked from Houston, as he watched Scott drive the LRV slowly away. The rover was underway, and there were smiles all around in Huntsville with the LRV team, and in Mission Control in Houston, which could watch Scott drive the rover from the images being beamed back to Earth from the temporarily stationary TV camera. The euphoria was short-lived, however, as Scott reported that he had no forward steering. At Allen's direction, Scott moved the Forward Steering switch to Bus "C." but to no avail. Scott was then asked to cycle the Forward Steering circuit breaker, but the astronaut reported no change as he slowly circled the LM.

"Roger, Dave," Allen responded. "Press on." The inherent system of redundancy demanded by NASA for the LRV to ensure mission success had just proven itself, but the Boeing engineers were baffled and vexed, and immediately set to work to debug the problem.

"On the very first EVA, Scott reported the front steering did not work," remembered Ferenc Pavlics. "I was in Houston at the time, and they rushed out to me and two engineers I had with me. They said, 'OK, come up with a checkout procedure to find out what is wrong.' So we did that and rushed the checklist to the CapCom. It was only minutes but by that time, they had decided to proceed with the mission with just the rear steering operational."

Scott had driven the rover around the LM and out of TV camera range. Jim Irwin followed him with the 16 mm Data Acquisition Camera.

Allen commented that the astronauts were not visible on the TV camera, so Scott got off the rover and loped over to the camera. He moved it slightly to the left, and viewers back on Earth were greeted with a spectacular image of the majestic Swann Range in the distance, named after Gordon Swann the Principal Investigator for Apollo 15 geology. Scott then began loading the front of the rover, starting with the telecommunications equipment that included the Lunar Communications Relay Unit (LCRU), the Television Control Unit (TCU), the High-Gain Antenna with its umbrella-like appearance and distinctive gold-mesh reflector, and then the Low-Gain Antenna. Scott announced he was moving the TV camera from to the tripod to the rover, which required disconnecting it from the cable running to the LM. The image was lost briefly while Scott moved the GCTA to its position at the front of the rover and then attached the cable from the TCU to the TV camera.

Scott verified it was hooked up and that was Ed Fendell's cue to put the TV camera through its paces. Fendell was chief of the Communications System Section of the Flight Control Division and it was his responsibility to coordinate all communication to and from the Moon, including frequencies from Al Worden in the Command Module, communication patched through the LM, and communication to and from the LRV. These communications were handled by Fendell's crew while

Ed Fendell was director of communications at Mission Control in Houston. He also was responsible for operating the Ground-Commanded Television Assembly (GCTA) for Apollo 15, 16 and 17. (Ed Fendell)

Fendell himself was in charge of operating the TV camera when the rover was at rest. The High-Gain Antenna had to remain aligned with the Earth within a very narrow field, which could not be maintained while the rover was underway. The astronauts aligned the antenna by looking through a sight until the Earth filled the small window. There was a common misconception that the TV camera was controlled using a small joystick. That was definitely not the case.

''On our console,'' Fendell stated, ''we had a panel to send commands, and under each button was a programmed command for the computer. We had a pan left, a pan right and a pan stop. Then we had pan increment right, and a pan increment left which would pan left 3 degrees and stop, or pan right 3 degrees and stop with one depression of the button. There was also an increment tilt of 3 degrees. And we had zoom in and zoom out. When I sent these commands, there was a delay of something like three seconds before the camera would respond. I had to anticipate what might happen a lot of times. The zoom was the big item because if the crew started to move, the best thing to hit first was the zoom. The zoom allowed us to keep up with them without them running out of the picture.''

Fendell panned the camera to the left to take in the LM *Falcon* and the impressive massifs in the distance, then performed a slow continuous pan counter clockwise to take in the surrounding lurain, until it came to a stop pointing almost directly aft of the rover. Irwin came into view on the right-hand side after having stowed the core sample tubes and caps at the rear of the rover.

"And the TV scene for us is breathtaking," Allen exclaimed, marveling at the TV camera's resolution and image quality.

"Good," Scott replied. "Can't be half as breathtaking as the real thing, Joe. Wish we had time just to stand here and look."

"It was amazing when the camera first came up and we started to move it," Fendell remembered. "The next thing I knew, I had a hand on my shoulder. It was Christopher Kraft, who was looking at the TV image and just shaking his head. Everybody in the control center came to a dead stop. They had no idea that this thing was going to look this good."

Scott and Irwin wished they had time to admire the Hadley-Apennine region that surrounded them. The indescribable blackness of space contrasted with the brilliant silver-gray of the lunar landscape and they stood knowing they were the only life on a barren, airless Moon that was billions of years old. Irwin was responsible for loading the geopallet and all the related equipment on the rear of the rover and after he had finished the loading, Scott took the dust brush to dust him off. Irwin had fallen and his lower suit was now covered with lunar dust. He would have to re-enter the LM to change some switch settings and stow the contingency sample, and he needed to be as dust-free as possible.

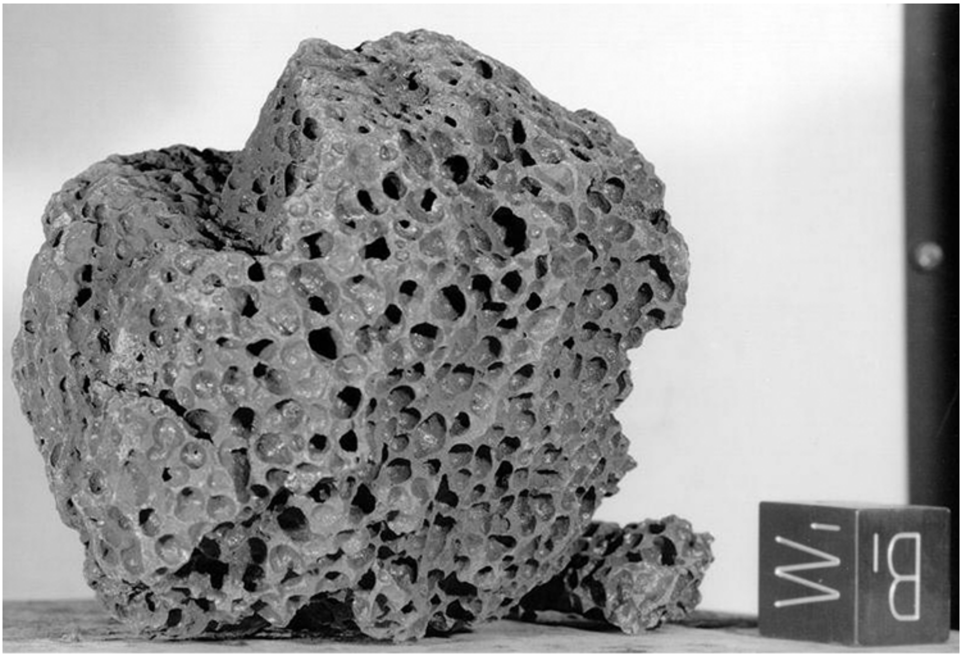
"Dave, this is Houston," Allen communicated. "While you are stowing the brush there, just thinking ahead, we've got a couple of checks to carry out on the rover before you drive off from the site."

"Yeah, that's good, Joe. Glad [to]," Scott responded.

"Roger," Allen came back. "We'll want you to look at the front wheel steering decoupling lanyard for us and then after that, physically try to turn the front wheels for us." Scott noted that the lanyard was taped down and that trying to move the front wheels produced no movement. The astronauts were about 25 minutes behind their timeline and Allen urged them to prepare to move out on their first traverse. Scott passed the lunar contingency sample up to Irwin, who stowed it in the LM while Scott returned to the rover and announced he was taking the TV camera off line, in preparation for the first EVA and to initialize the navigation system. Irwin returned from the LM and both astronauts mounted their Hasselblad cameras to their chest mounts. Then they climbed onto the rover, buckled their seatbelts and set off on the first traverse of EVA No. 1.

Because the crew was some 25 minutes behind the planned schedule, Scott drove with deliberate speed southwest to the edge of Hadley Rille, and would then follow the rim of the Rille toward Elbow Crater and their Station 1 stop nearby. Scott found the LRV to be very nimble in $\frac{1}{6}$ -G, even with just rear steering. Four minutes into the first traverse, he reported the LRV's performance to Houston.

"The Rover handles quite well. We're moving at an average of about eight kilometers an hour. It's got very low damping compared to the one-G Rover, but the



Mare Imbrium basin was formed 3.8 billion years ago from the impact of a comet or asteroid, which created the Apennine Mountains and caused molten material to rise to the lunar surface and spread out, eventually cooling. Sample No. 15556 is a vesicular basalt having many gaseous bubble pockets. (NASA)

stability is about the same. It negotiates small craters quite well, although there's a lot of roll. It feels like we need the seat belts, doesn't it, Jim?''

''Yeah, really do,'' Irwin responded.

''The steering is quite responsive even with only the rear steering,'' Scott continued. ''It does quite well. There doesn't seem to be too much slip. I can maneuver pretty well with the thing. If I need to make a turn sharply, why, it responds quite well. There's no accumulation of dirt in the wire wheels.''

''Just like in the owner's manual, Dave,'' CapCom Allen answered.

''Well, we were bouncing and skimming along,'' Irwin wrote in his memoir, ''and to our amazement no dust was being thrown up. The big concern had been that we'd be surrounded by a cloud of dust that might keep us from seeing where we were going and prevent us from making any observations. Not so. The fenders worked like a dream in keeping the dust down.

''At one point we came over a little rise and there was a crater about twenty feet deep right in front of us. Dave made a quick left turn that threw the vehicle right up on the two right wheels. I felt sure we were going to flip. What if the thing did roll over and pin us underneath it? Could we ever release those seat belts so we could get out from under and turn the Rover back over? We never had to find out.''

Scott quickly learned that he could not take his eyes off the route directly in front

of them at the speed they were traveling because of the blocks and subdued craters. Driving the LRV required focused concentration, but the spectacular panorama in front of them made this difficult. Irwin had the task of looking wherever they drove and describing to Houston what he saw. He also conducted geologic observations while Scott was driving. The two astronauts finally spotted Hadley Rille and while Scott drove along the edge of the Rille, Irwin gave detailed descriptions of their observations. Both exclaimed how large the Rille was, at approximately 300 meters deep and over 1.5 kilometers wide. Allen asked Scott how the rover was handling with the loss of front steering.

"Apparently, your front wheels are tracking straight ahead, is that correct?" Allen asked.

"That's correct," Scott responded. "And, of course, when we turn, they dig in, and it makes the rear end break out. But it's okay; we can handle it."

It was then the two astronauts got the same idea of perhaps venturing down into the Rille with the rover, and decided to have some fun with their CapCom.

"I might add to Jim's comment," Scott told Allen, "that the near side of the Rille wall is smooth without any outcrops, there by St. George. The far side has got all sorts of debris. It almost looks like we could drive down in on this side, doesn't it?"

"Stand by on that, Dave," Allen cautioned, obviously worried. Irwin decided to really give Houston a start.

"I'm sure we could drive down," Irwin added. "I don't think we could drive back out." Both astronauts chuckled at that, knowing Mission Control was alarmed at the possibility. In truth, each EVA was very carefully established and would be followed according to their Cuff Check List. Driving into the Rille was not part of the plan. The idea was discussed in the traverse planning meetings because of the variety of rocks that could be collected that had rolled down the sides of the Rille. However, doing so entailed considerable risk as the angle of the Rille walls could exceed the rover's hill-climbing ability. The idea was discarded in the discussion meetings.

Scott drove on to Elbow Crater, and soon found it, though it had not been easy to spot because it was such a subdued crater. He stopped the rover and the astronauts unbuckled their seatbelts and dismounted for their Station 1 sampling and photography. Scott aligned the High-Gain Antenna toward Earth to permit video of their activities and in Houston, Ed Fendell punched the controls to bring the TV camera to life and begin the pan of the area.

"When you see the pictures at each stop," said Fendell, "you'll notice that the first thing that happened is an almost 360-degree pan in 3-degree increments. That was something that was worked out between me, my guys and the USGS guys who were doing that for the Lunar Surface Team in the Backroom. We did a Wide Angle Pan (WAP) at every site. At the Lunar Module or when the crew pulled up to a site, the first thing we did was a complete pan in 3 degree increments. The team in the Backroom would take a Polaroid picture of the TV set each time the camera stopped. Then they pasted those photos together so they would have something in front of them on their desk so they could request things they wanted to see for their planning. They did this because they couldn't get the videotape back soon enough from the TV people. This gave them a complete panorama of each station stop."

Scott commented that there was a fair amount of dust on the rover from their traverse, and Irwin complained there was so much dust on his camera that he could hardly see the camera settings. The astronauts spent fifteen minutes at Elbow crater taking their samples and additional photographs. When they discovered a desirable rock they wanted to collect, Scott would hold the sampling bag and Irwin would pick it up with the tongs and place it in the bag. They were always careful to call out the sample bag number. More interesting discoveries awaited, however, and they were admonished by Allen to proceed onto St. George Crater. Already, the astronauts had learned that the first order of business once on the rover was to fasten their seatbelts.

"Okay, Joe, the time consumer here is the seatbelt operation," Scott told Allen, "because we definitely need them; and in $\frac{1}{6}$ -G, we don't compress the suits enough to be able to squish down and get the seatbelt locked without a certain amount of effort."

"Roger. We understand," Allen responded.

"I'll tell you, it's a good seatbelt design," added Scott. "It's a great seatbelt design. Okay, let's check the Drive Enable. They're all on. Drive Power is on. Steering Forward to Bus A. Fifteen Volts DC. Ready to go, Jimmy?"

"Ready," Irwin answered.

It took Scott and Irwin about seven minutes to drive to St. George Crater, which was Station 2 of EVA-1. They got off and Scott once again oriented the High-Gain Antenna and powered up the TV camera. Fendell brought the camera up to begin surveying the area around Station 2 while Scott and Irwin began examining a large rock up slope of where they parked the rover. The massive Rille dominated their view down slope and Scott could not help himself, exclaiming it was the most beautiful thing he had ever seen. The stark beauty of the Moon was something virtually all the astronauts would comment on during their explorations. As Fendell focused the camera on the rock Scott and Irwin were examining, Joe Allen ventured a guess that the rock was probably not older than 3.5 billion years old.

"Can you imagine that, Joe? Here sits this rock, and it's been here since before creatures roamed the sea in our little Earth," Scott marveled. The thought must have occurred to Scott that the rock he was looking at had been resting at that location undisturbed for a duration of time that was nearly inconceivable to the human mind. It also occurred to him that after billions of years, he – Capt. David R. Scott – was about to move it from its position of nearly eternal rest. He reveled in that moment in time as he turned the rock over to examine the soil beneath. At this stop, the astronauts employed a new tool, a rake designed by geologist Lee Silver. The rake permitted lunar soil to pass through but retained pieces of rock larger than half a centimeter. The astronauts put the rake to good use during their three EVAs. Scott and Irwin took samples broken from the rock and then took core samples using the core tubes that Irwin drove into the lunar surface with the hammer. The core tubes were removed, each end was capped and they were then returned to the rover. The astronauts were on the slope of Hadley Delta near the rim of St. George Crater for over three-quarters of an hour.

Returning to the Lunar Module

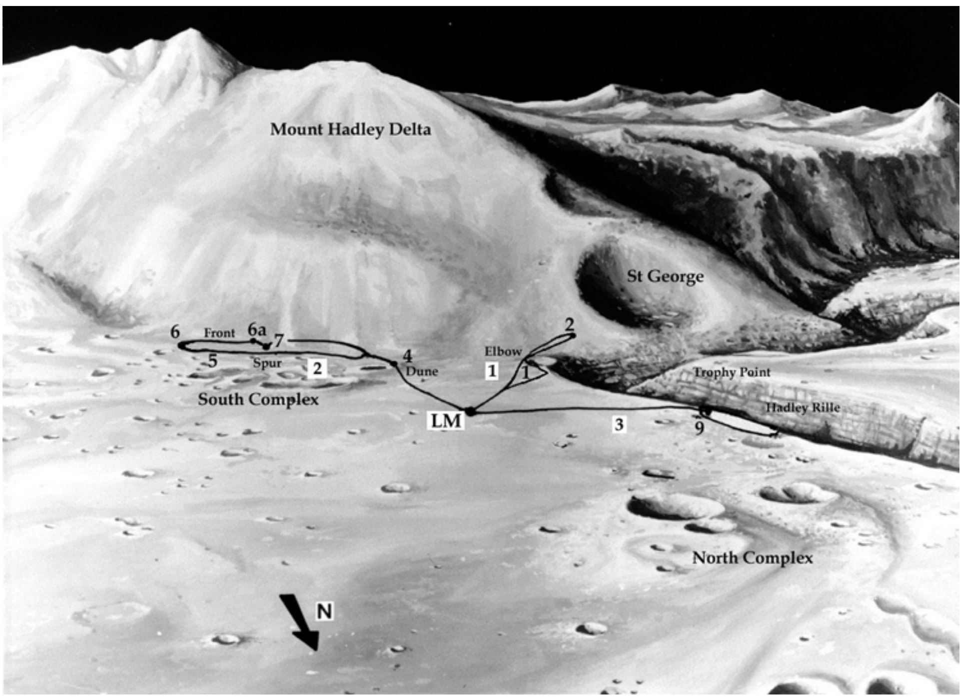
Joe Allen announced that the Station 3 stop was being eliminated and directed the astronauts to return to the LM in order to deploy the surface experiment packages. Because the astronauts would return to the base of Hadley Delta in the specific area of the Apennine Front during EVA-2, it was felt that there would be no loss of science. Scott and Irwin climbed onto the rover and prepared to return to *Falcon*.

"We suggest you just follow your navigation system home," Allen told the lunar explorers.

"That's a good idea," Scott answered. "I was going to say we might try that just to see how she works."

"That's exactly our thinking," Allen replied. Once they were strapped in, Scott and Irwin relied on the LRV's navigation system to give them their proper heading. They had a commanding view in front of them because they were at the highest elevation of their first EVA. However, they could not see the Lunar Module from their location because of the much closer horizon caused by the Moon's smaller diameter relative to the Earth.

"One thing we were always somewhat aware of," Scott recalled during the interview with the author, "was that when you are on the Moon you go over the



This illustration depicts the actual station stops during each EVA Scott and Irwin made with the Lunar Rover. They had hoped to stop at the North Complex and climb Schaber Hill with the rover during EVA-3 but time did not permit. (NASA)

horizon quickly and you don't see the LM. We were the first crew to travel over the horizon and be out of sight of the LM – a big change in planning and preparation. And so on our first excursion, the backup navigation to get back to the LM was the old 'Hansel and Gretel' trick of following your tracks. Once we were comfortable after the first EVA, then we'd take a side excursion and come back a different way. But in the process of planning this, we knew to use the Sun compass, so that if the navigation system broke down or didn't work, we could still find our way back. But the system worked brilliantly on the Moon, although you had to have some method of navigation other than your tracks and the rover system itself."

With the front steering inoperative, steering the rover on the lunar surface was a delicate procedure. As they were descending the side of St. George Crater, traveling at only five kilometers per hour, Scott maneuvered to avoid some blocks and the rover spun around.

"You can't go fast downhill in this thing," Scott told Houston, "because if you try and turn with the front wheels locked up like that, they dig in and the rear end breaks away, and around you go. And we just did a 180."

As Scott turned the rover around and continued his return to the LM, the GM and Boeing teams at the Cape and in Houston redoubled their efforts to resolve the problem of the inoperative front steering. Seven-and-a-half minutes into their return, the astronauts spotted a reflection off the LM, directly ahead of them. The navigation system was working perfectly, and Scott grew increasingly comfortable driving the LRV.

"It's easy to drive," Scott told Allen, "no problem at all. We just have to be careful because of the locked front wheels, but other than that, it's very responsive. I can put the throttle right up to the stop or at some intermediate position; and take my hand off and rest my hand. If I want to go left or right, I just put a little pressure until I get the angle I want and then let it off and we re-center on the steering. It's really neat, even with the locked front wheels."

"Sounds mighty smooth, Dave," Allen concurred. "And we're still working on your front wheel problem. We may have them back before you know it."

Less than two kilometers from the LM, Scott spotted a small vesicular basalt rock that caused him to literally stop in his tracks. The rock was striking, with its dark black appearance. Exercising his prerogative as Commander, Scott decided he had to have it as a sample, but feigned a problem with his seatbelt, knowing Allen would probably discourage him from taking the time to get the sample. Irwin immediately caught on, first complaining about having dropped his map. While Scott went to the rear of the rover to get the sample tongs and then walked over to the desired sample, Irwin launched into a description of some of the craters he had observed for the benefit of Houston, but also to cover for Scott, who was photographing the area before and after taking the sample. Scott then returned to the rover, stowed the tongs, placed the bagged sample under his seat and climbed back onto the rover. CapCom Allen suspected what was actually going on but said nothing, and the geologists in the Backroom exchanged knowing glances. In less than two minutes, Scott had accomplished an unplanned sample collection, including the photography. The speed and ease with which Scott was able to accomplish this was the result of the

functionality and operability of the LRV's crew station and the ability to get off and on easily. This had been conceived, planned and rehearsed for lunar operations. Back on the rover, Scott was able to buckle his seatbelt quickly, and they resumed their return to the LM. Just over half-an-hour after leaving St. George Crater, the astronauts were back at their Lunar Module.

Their task now was to deploy the Apollo Lunar Surface Experiments Package (ALSEP). The astronauts choose a site 100 meters from the LM to deploy the ALSEP. First the Central Station was placed, followed by the Radioisotope Thermal Generator which supplied the power for the ALSEP. The experiments deployed included the Passive Seismic Experiment, the Lunar Surface Magnetometer, the Suprathermal Ion Detector Gauge, the Lunar Dust Collector, the Heat Flow Experiment and the Solar Wind Spectrometer, which Scott deployed just prior to re-entering the LM. The Heat Flow Experiment required two holes to be drilled in the lunar surface to a depth of 3 meters. Problems with the drill stems removing soil bogged the drilling operation down and Scott could get no further than 1.7 meters in depth. He tried to drill a second core, but with the same result. Scott thought he had hit a large rock, preventing him from drilling deeper, but it later turned out that it was a design flaw in the drill stem. Removing the drill stems proved just as much of a chore and consumed more time than had been planned for. Scott had parked the LRV near the ALSEP deployment site so the activity could be watched by Houston and once it was completed, Scott and Irwin boarded the rover again. In order to save precious time, they did not take the time to fasten their seatbelts. Getting on and off the rover in $\frac{1}{6}$ gravity in a stiff pressure suit was considerably different than their training on Earth, where they had the benefit of the Earth's gravity and the suits were not pressurized. They could not bend the suits at the waist easily sitting on the rover while on the Moon. Scott drove the rover at less than 5 kph so that they would not be tossed from their seats. Despite the effectiveness of the LRV's fenders, there was still a coating of lunar dust on the vehicle.

"Okay, Joe, there's quite a bit of dust on the mirror on the LCRU," Scott told Houston. "As a matter of fact, there's quite a bit of dust all over the Rover. It's a very fine kind of dust. Do you want us to brush that off?"

"Dave, maybe a token effort, but don't take too long; it doesn't sound too serious to us," Allen assured Scott. After some rudimentary dusting of the rover, Allen directed Scott to completely open the LRV battery covers, open the LCRU blanket thirty-five per cent, and then power down the LCRU. Scott asked Houston what he could do with the time remaining. The Solar Wind Spectrometer had yet to be deployed and Houston suggested he do so. Although he had not trained to deploy the experiment for the mission – this was Irwin's task – Scott had done so in training as backup for the Apollo 12 crew. He had Irwin talk him through it, however, and the experiment was deployed in five minutes.

There was still a most important duty to perform before closing out EVA-1, which was to plant the American flag and take the requisite photographs. The Hadley-Apennine region proved most photogenic. The color photo taken by Irwin of Scott saluting the flag, with the Lunar Module *Falcon*, the Lunar Rover and Hadley Delta looming in the background, has become an icon of Apollo photography. This photo

was actually taken at the start of EVA-3 with a new color film magazine in Irwin's camera. The position of all these elements were actually carefully worked out in the simulator building at KSC months before. The only difference was the orientation of the rover, which was changed to provided better battery cooling between the second and third EVAs.

The lunar samples were safely secured inside one of the Sample Return Containers (SRCs), known as a "rock box." Scott re-entered the LM, the cabin was re-pressurized and the astronauts then went through the process of removing their suits. The astronauts communicated with their Command Module Pilot, Al Worden, and told him of the success they had had. Scott and Irwin spent the next several hours organizing their cramped quarters, cleaning up as much as possible, having their food bars and drinks, and discussing their day's activities with Houston before finally going to sleep.

EVA-2: EXPLORING THE APENNINE FRONT

Scott and Irwin both had a good night's rest, although on the nearside of the Moon, the Sun never sets. The crew got their wakeup call from CapCom Gordon Fullerton, who moments later handed over the CapCom duties to Joe Allen. The crew discussed the day's plans for the scheduled six-and-a-half-hour EVA-2 with Allen, and went through a long list of items on the check list prior to donning their suits and depressurizing the cabin. The astronauts egressed from *Falcon* and went about their tasks preparing the rover for their second EVA. Scott and Irwin kept communication flowing to CapCom Joe Allen, who helped the crew in their sequential planned chores.

"Joe," Scott said to Allen, "I'm in a position to take another crack at that steering, if you'd like to talk me through the procedures."

"Okay, Dave," Allen responded. "We want you to exercise the Forward Steering switch by cycling from Bus A to Bus C and back several times, and then stop with the switch finally at Bus Charlie."

"Steering Forward is now in Bus Charlie, and I cycled it three times" Scott answered.

"Okay, Dave. Now proceed with your normal power-up cycle if you haven't already; and give me a call when you're ready to start driving."

The astronauts finished the items on their Cuff Check List. Scott performed the Bus cycling procedure once again, and then moved the T-handle. The front steering responded.

"You know what I bet you did last night, Joe?" Scott asked with amazement, "You let some of those Marshall guys come up here and fix it, didn't you?"

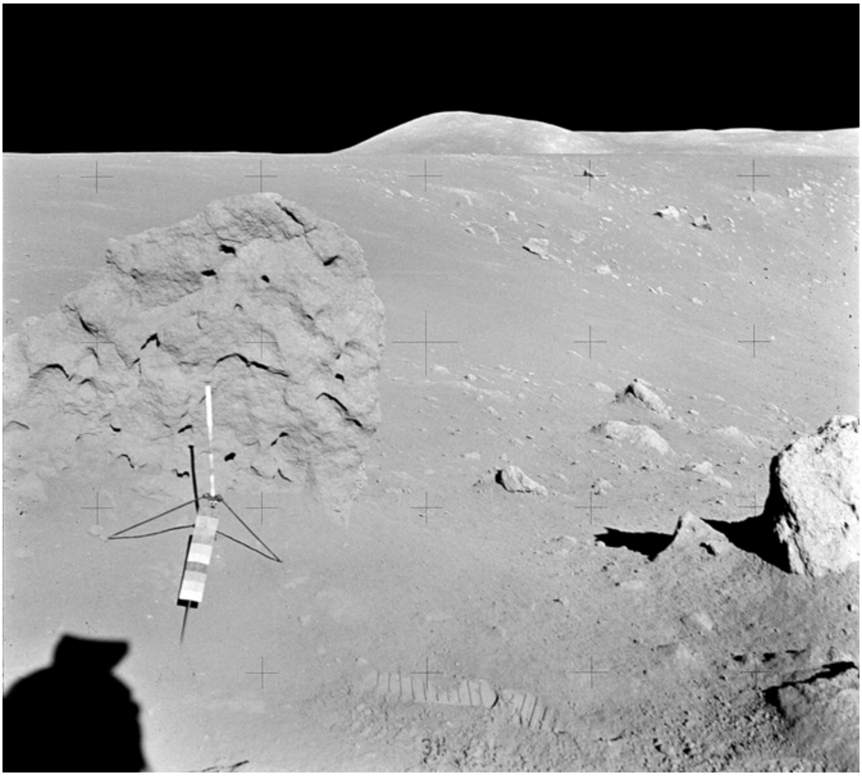
"They've been working, that's for sure," Allen replied, smiling.

"It works, Dave?" Irwin asked, incredulous.

"Yes, sir. It's working, my friend," the Commander answered.

"Beautiful," Irwin said.

"Lot of smiles on that one, Dave," Allen radioed. "We might as well use it today."



One of the most intriguing discoveries the LRV made possible was this vesicular boulder. It was photographed by Dave Scott at Station 4 during EVA-2, within the South Cluster near the foot of the Apennine Front. (NASA)

"Boeing has a secret booster somewhere to take care of their Rover!" Scott exclaimed. He drove the LRV away a short distance to a level spot to reset the navigation and told Allen that the rover operated so much better with both forward and rear steering. Many people remained baffled over the forward steering anomaly, but Sam Romano and Ference Pavlics at GM both suspected what the problem might actually have been.

"Our suspicion was," Pavlics recalled, "that because the Lunar Module landed in a fairly early part of the lunar morning and the vehicle was sitting in a shaded area, the temperature was still very cold in that shade. Because of the cold temperature, the conductive plastic potentiometer which was controlling the steering function did not make contact. So our recommendation was just to exercise the joystick back and forth, left and right many times to heat up and possibly reestablish electrical contact. That probably happened as the system warmed up."

The astronauts continued their preparations for the day's station stops. Based on the results of their explorations during EVA-1, Station 4 and Station 5 would be eliminated from this traverse. Their first stop was Station 6 at the base of the

Apennine Front. Scott found that driving the rover with the dual Ackermann steering operating was almost too much when traveling at more than 5 kph.

"Hey, Joe, the steering is a new task," Scott observed. "It's really responsive now. I guess I got pretty used to quiet steering, and this thing really turns!"

"Roger, Dave. We don't want it to be too easy for you," Allen replied.

"Hey, look. We can always disengage the rear steering," Irwin told Scott

"No, I'll get used to it. It's just a matter of getting used to," he reassured Houston. However, Scott found the LRV to be almost too sensitive with both front and rear steering, and wanted to try it with just front steering. He brought the rover to a stop to disengage the rear steering, telling Houston that the double Ackermann steering was too responsive when traveling at speed and with a lack of traction due to the wheels leaving the ground over bumpy lunar surfaces. The seatbelts were continually proving their worth.

"You get this floating sensation on the Moon," Scott said during this author's interview, "and you've got to have the seatbelts or you float right out of the seat. That became apparent very early. And then you get a lot of feedback through the suit when you're on a bumpy surface because you are tied to the rover by the seatbelt. Through the suit your arm feeds back into the hand controller, which was sort of a challenge. Because of the feedback of the bumps, you're constantly changing the steering, and even the speed. So, that was one of the things we had to be careful of."

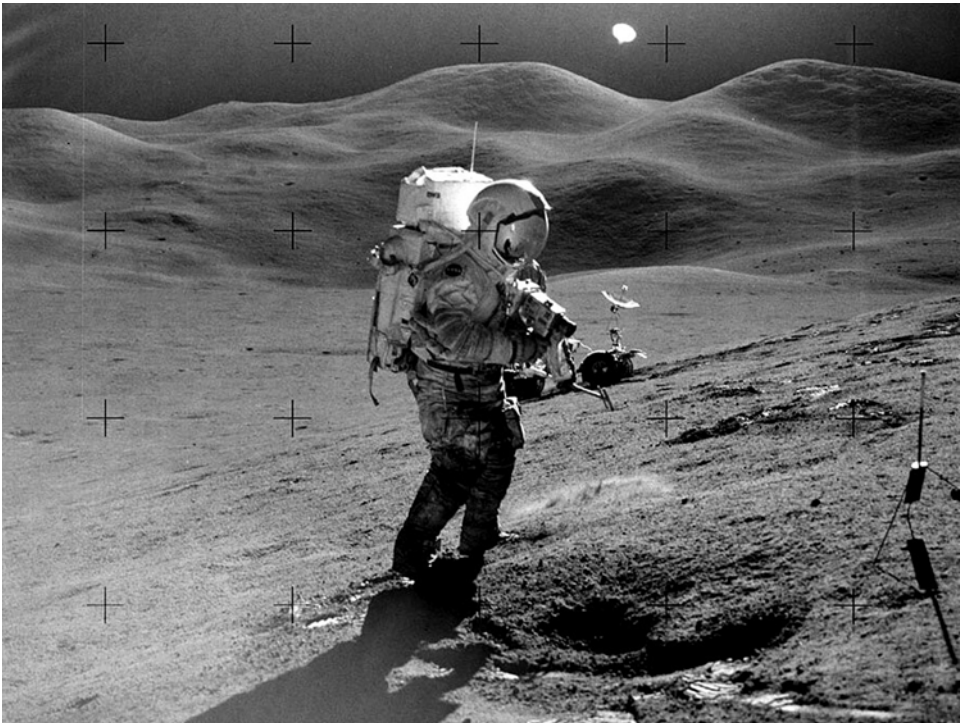
Station 6 and 6A

Based on the revised EVA plan sent from Houston, Scott and Irwin would travel due south toward the South Cluster of craters. They would temporarily skip the Station 4 stop there, as well as the Station 5 stop near Front Crater at the Apennine Front, and go directly to Station 6 at the Front. Despite the undulating lunar surface, which was pockmarked with craters and blocks, Scott managed a brisk 9 kph. The two astronauts kept up a running description during the traverse toward Station 6.

"A crater on our right now about 50 m in diameter with a lot of gray fragments on its rim," Irwin commented to Houston, "and we're just passing one [rock] that's sitting right on the surface – about two feet, sub-angular. I can look out now and see the South Cluster and I get the impression of perhaps some horizontal beds in the first mound in the South Cluster. I do see a lot of blocks over in that direction; particularly the second mound – the west side of the second mound that appears to be in the Secondary Cluster."

Scott and Irwin headed directly for Dune Crater, then skirted the rim of the crater by traveling counter clockwise. Despite its size, Dune Crater proved surprisingly subdued, according to Scott.

"We're on about the southwest side, now, of Dune Crater," Irwin continued. "As Dave mentioned, we're heading 155 now. A very fresh crater at our 1 o'clock position with a lot of angular blocks; very slight raised rim about two feet above the general surface, but a very fresh crater. It seems like the albedo was lighter around that one than others that we've seen. In fact, you might be able to see that on your map, Joe. The lighter albedo in the southwest side of Dune."



During the Station 6 stop on EVA-2, Irwin photographed Scott on the slope of Hadley Delta. Note the angle of the LRV. In the distance is the Swann Range, named by Scott after USGS Principal Investigator for Apollo 15, Gordon Swann. (NASA)

The geologists were also following along with their maps, but waited in anticipation for the Station 6 stop, where everyone could watch the TV images. Irwin and Scott continued south toward Spur Crater, but after more than twenty-six minutes of driving the rover, Scott told Allen he needed to stop and rest. The rover had really been taking a pounding from the wheels hitting the blocks, Scott was constantly working the hand controller to avoid the largest ones, and his concentration on the driving itself was fatiguing. Scott instructed Irwin to remove his camera from its mount and take a series of photos while panning. While Irwin did this, Scott took the opportunity to nibble on his food stick and drink some water. Refreshed, Scott resumed the traverse toward Station 6, which he reached sixteen minutes later. He had been driving for nearly three-quarters of an hour. Surprisingly, Scott reported that the battery temperatures were 75 and 81 degrees, and the drive motor temperatures were off-scale low, meaning they were running cool.

Scott had driven up the Apennine Front and parked the rover about 100 meters above the mare plain. Irwin got off and took a series of photographic pans that were among some of the most striking of the entire mission. The astronauts could see their Lunar Module *Falcon* roughly 5 km distant on the Hadley plain. Scott aligned the TV High-Gain Antenna, and shortly thereafter, Mission Control was treated to the

spectacular vistas from Hadley Delta. In between photographs, the astronauts began their sample collection above the rover's parked location. Scott displayed his excellent sample recognition and descriptive abilities to Houston as he and Irwin picked up rock samples.

"The first one here is a fine-grain breccia – a micro-breccia – and it's got, it looks like, a third order with white clast in it. The matrix is dark black and it has glass within a fracture on the side, not unlike some of the 14s," Scott observed, referring to samples returned from Apollo 14. Scott continued his detailed description with the second sample.

"This is definitely a different kind of breccia, Joe," Scott added. "It's only got light gray millimeter-size clast in it with fine-grain gray matrix, and the clasts are about ten per cent of the total frag, so it's somewhat different."

Scott and Irwin spent about an hour collecting samples, and Scott was even able to collect a core sample from the rim of a small crater below the rover with relative ease. This EVA resulted in significant soil accumulation on the LRV, elevating the temperatures on the communications equipment.

"Before we leave this area, we want you to brush the LCRU and the TV camera lens," Allen instructed the astronauts. "We're running quite hot on the LCRU and think there must be a lot of dirt on it."

"Running the TV camera was really intense," Fendell admitted. "When the astronauts stopped and you took control of the camera, you didn't fool around and you didn't take your eyes away for an instant. We had a TV monitor up on the console, as well as the big screens at the front. If you turned away, it was all over. It was pretty intense staying focused on the job."

Scott and Irwin continued filling sample bags with soil and taking more pictures before walking back to the rover to stow their samples and equipment. Ed Fendell had already positioned the TV camera in the stowed position looking at the battery covers. At Allen's comment, he panned the camera to the right toward the LCRU which revealed a layer of dust completely covering the mirrored LCRU radiator. Irwin took the brush and first cleaned the TV lens which made a dramatic improvement. He then brushed the radiator on top of the TV camera and then he slowly brushed the dust from the LCRU radiator, revealing its mirrored surface with each brush stroke, visible in the TV images beamed back to Earth. Irwin then tilted up the TV camera and made a second pass with the smaller TV lens brush.

"Would you check the oil too, please?" Allen joked. Irwin chuckled. At this moment of the mission, Allen's comment, while said in humor, truly reflected the overall mood at Mission Control in Houston as to how well Apollo 15 was actually progressing. It revealed a level of confidence in the equipment and satisfaction in the crew that was in fact the result of stringent engineering, testing, years of training and rigorous management. Apollo 15 was already an astounding success, and more discoveries awaited. Scott completed his 500 mm photographs and Irwin changed out a jammed film magazine in the 16 mm Data Acquisition Camera. Irwin then climbed into his seat and then the Commander climbed on, buckled himself in and drove west toward a boulder on the side of Hadley Delta. This stop was identified as Station 6A.

As the astronauts got off the rover again, they were impressed with the severity of the slope, and had to lean into the hill to maintain their balance. Trying to align the High-Gain Antenna with Earth, Scott knew, would prove very difficult, so he told Allen that he would bypass the television for this station stop.

"Okay, Dave. Whatever you say," Allen acknowledged, understanding. The geologists in the science support room were not happy with that announcement, but they would have to be content with the audio feed and examining photographs when the crew returned. Allen asked Scott if this was because he could not get into the right position to align the antenna with Earth.

"Yeah, that's right, Joe," Scott answered. "The slope is real steep and, like I mentioned before, the sighting device doesn't transmit enough light to really make it very easy to find the Earth. I think it would take me a couple of minutes just to find you, and I think you've seen the same thing. But if you would like, I'll give it a try."

Allen advised him to proceed with the sampling without having to align the antenna. Scott had parked the rover above a boulder a safe distance, but after making a practice descent halfway down toward the boulder, he decided he would move the rover closer. Scott had to cautiously side-step his way back up to the rover. He got on, buckled himself in then flicked the switch on the hand controller to reverse. He pulled back gently on the hand controller and backed up slowly. Scott could not see behind him, and Irwin, standing nearby, guided him with brief verbal cues. Scott wanted to move far enough to be able to turn the rover, travel down slope, then park it just below the boulder. The loose lunar soil was deep, and Scott very slowly drove the rover down to its new position. He parked it cross-slope and got off and Irwin moved over to the rover to keep it from sliding. The rover's left rear wheel was actually up in the air. Irwin actually asked Scott if he was afraid they might lose the rover on this steep slope. With absolutely no television images being beamed to Earth and only audio being heard, the scene in Mission Control and the Backroom must have been tense at this point. Allen implored Scott to make an attempt to align the High-Gain Antenna as best he could so Houston could try to capture some live TV of their situation, but the brief stop, coupled with the steep slope conditions did not make aligning the antenna a priority for this stop, and Houston agreed.

A spectacular discovery at Station 7

Scott did succeed in taking a sample from the boulder, which had a subtle green cast from an abundance of magnesium oxide present – a totally unexpected find. After collecting samples from the boulder, Scott drove the rover to a more level surface, Irwin got on, and they drove on to Spur Crater and Station 7. The crew had spent just under half-an-hour at Station 6A, but it had been a nervous time for Mission Control without any "eyes" to see what Scott and Irwin had to deal with there.

At Station 7, the first order of business was aligning the antenna, and once again Houston had eyes on the Moon. The two astronauts were taking samples near the rim of the crater when they made one of the most momentous discoveries of the mission as they examined one sample in particular.

"Almost see twinning in there!" Irwin remarked.

"Guess what we just found. Guess what we just found!" Scott told Allen excitedly. "I think we found what we came for."

"Crystalline rock, huh?" Irwin asked.

"Yes, sir. You better believe it," Scott replied.

Scott and Irwin had discovered an anorthosite with a crystalline structure known as twinning. This meant it was in all likelihood a piece of the Moon's early crust. They carefully bagged this and noted the bag number for Houston. Dating the sample back on Earth revealed that it was more than four billion years old. They took rock, soil and rake samples, as well as a chipped sample from a boulder at Station 7. After three-quarters of an hour there, Joe Allen implored them to head on to the original Station 4 on the south rim of Dune Crater for samples and photography before heading back to the LM. They reached the planned Station 4 stop and, with Houston's concurrence, agreed to forego the antenna alignment and TV transmission due to the brevity of the stop (planned at ten minutes) they would make for sample collection and photography. The actual time spent at the station was seventeen minutes, after which the astronauts re-boarded the rover and headed back to *Falcon*. The Lunar Roving Vehicle was also proving to aid the astronauts by providing a welcome period of rest as they traveled between stations. They could see the Lunar Module in the distance, and beyond it, the Pluton Crater and the North Complex were visible. The astronauts liked crediting certain lunar features after the geologists who worked with them in planning the traverses, and Scott took this moment to recognize Gerald "Jerry" Schaber.

"Okay, now we'll take a little left here, and ... we can look at Pluton," Scott commented. "We'll see Pluton all the way and the LM is silhouetted right against the base of the crater so we can't miss that. Just to the right of it is Schaber Hill which we'll be heading for tomorrow."

Closeout of EVA-2

At this point in their return traverse, Scott and Irwin were relying entirely on the LRV's navigation system. They had followed their outbound traverse tracks around the western edge of Dune Crater, but left them behind as they headed due North. They would not see their original tracks again until they had passed Arbeit Crater on their left, when they could follow them back to the LM. Joe Allen briefed them on the off-loading of the lunar samples and core tubes back at the Lunar Module, and the other steps they would have to take once they got there. Their workday was far from over. Irwin would be busy performing soil mechanics experiments which occupied five detailed pages on his Cuff Check List. These were designed to determine the soil's ability to bear load and its general stability. Scott once again tackled the drilling, but the second drilling exercise to place the other heat flow sensor proved just as difficult as the first. Nevertheless he placed the second sensor, even though it was not as deep as the scientists had hoped. Scott then helped Irwin with the trenching experiment, which achieved a depth of roughly 25 cm before hitting a rock.

Joe Allen then informed the crew that the ALSEP site would become the de facto Station 8 stop, where the deep core sample was originally scheduled to be taken.

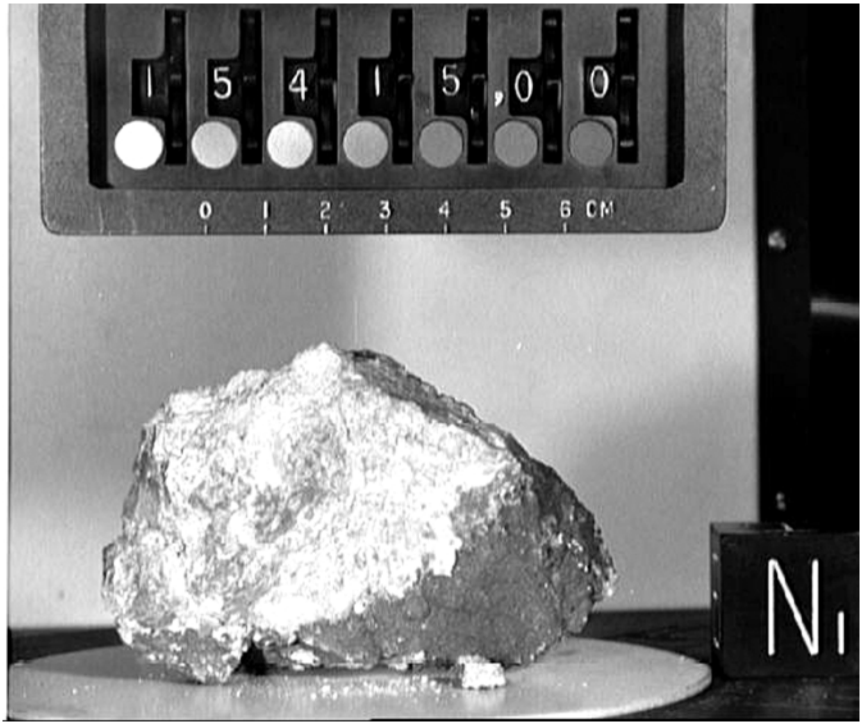
Scott was surprised at this, thinking this task had been bypassed by Houston. Nevertheless, he turned to the task of having to drill a deep core sample. Surprisingly, he succeeded in drilling down to a depth of 2.4 m after only a few minutes of effort. However, when it came time to extract the core tube, it could not be removed. Scott spent precious time trying to pull it out but the Moon held its grip on the core tube sections. Houston advised him to leave them there for the time being and another attempt would be made the following day. Meanwhile, Irwin took photographs of the various experiments at the ALSEP site. When both astronauts were back at the LM, Allen asked Scott to give the LRV a good dusting, including the LCRU, the TCU, the battery covers and the top of the TV camera.

Allen once more reminded the crew to dust off the LRV battery covers prior to opening them to let the batteries radiate to deep space. They continued with their closeout of the EVA, getting the lunar samples in the rock bags and core tubes up to the Lunar Module. Scott powered down the LCRU and opened its blankets and made sure that the TV camera was in the down position and powered off. Scott and Irwin climbed back into the Lunar Module, and re-pressurized the cabin at 149 hours and 26 minutes, Ground Elapsed Time (GET). They had set a new EVA record of 7 hours, 12 minutes and 53 seconds. The bad news was that they only had twenty-two hours left on the lunar surface, which was dictated by the limited lunar surface time of the Lunar Module. The next day's EVA would have to be shortened, and that put the hoped-for trek to the North Complex in serious doubt. The crew spent the next several hours going through the detailed closeout procedures with CapCom Gordon Fullerton. During this time, Scott and Irwin had the chance to communicate with their Command Module Pilot, Al Worden. They only had a few minutes to speak, but Scott used it to rave about the performance of the rover.

Certainly, Wernher von Braun was pleased with how well the mission was going, and gratified that the Lunar Rover had performed so well up to this point. Morea and his team were all smiles, as were the engineers and managers at Boeing and GM. Nevertheless, the LRV's thermal team kept a watchful eye on the temperature of the subsystems as Scott and Irwin finally bedded down for the last "night" on the Moon.

EVA-3: RECOVERING THE DEEP CORE SAMPLE AND RETURNING TO THE RILLE

CapCom Joe Allen awoke Scott and Irwin at just after 160 hours Ground Elapsed Time. Allen and Scott actually conversed in German for a minute or two, which warmed the hearts of Dr. von Braun, Dr. Kurt Debus, and many of the other original German engineers who worked on Apollo. Both astronauts had slept well and Allen updated the crew, stating that their first task was to retrieve the deep core tube, followed by the planned LRV Grand Prix photography before starting out for Station 9. They exited the Lunar Module, finished preparing the rover, then drove over to the ALSEP site to once more attempt to extract the core tube, which had a design flaw in the flutes at the core tube joints. After repeated strenuous efforts, Scott and Irwin finally succeeded in pulling the core tube from the ground, but at the



The Lunar Rover permitted Scott and Irwin to discover samples of the lunar crust that pre-dated the Mare Imprium impact. While at Spur Crater on Mount Hadley Delta during their second EVA, they spotted this anorthosite. It was found to be more than 4 billion years old. (NASA)

cost of a minor shoulder injury for Scott and the eventual blackening and loss of several fingernails. The frustration didn't end there. Scott managed to separate the first three sections of the core tube, but the last three sections were recalcitrant. The device at the back of the rover designed to help separate the sections had actually been manufactured backwards and thus could not properly grip the core tubes. Scott and Irwin spent an exasperating, time-consuming and precious half-hour trying to separate the sections, to no avail. Scott asked Houston if all the effort for this core tube was really worth it and Joe Allen assured him it most certainly was.

"Quite seriously, Dave and Jim," Allen told them, "that's undoubtedly the deepest sample out of the Moon for perhaps as long as the Moon itself has been there."

The first Lunar Grand Prix

Houston decided to simply leave the three-section core tube on the surface, to be retrieved later. Scott and Irwin then prepared to perform the LRV Grand Prix, with Scott driving the rover and Irwin filming the performance exercise using the 16 mm Data Acquisition Camera.

"Jim and I decided we'd conduct the drive test like a flight test," Scott said in the interview with the author, "the first flight test of an airplane, where you check performance, stability and control. And so we set up this track, which we attempted to film, but the 16 mm camera didn't work. We set up this lunar Grand Prix so that we could evaluate both the performance and the handling qualities in a relatively quick period of time. Jim would photograph everything and we commented as we were doing it. It was a good way to find out how the rover was going to perform before we set out on a traverse."

During a maximum acceleration run, Scott achieved a rooster tail of lunar dust 3 meters high that shot forward of the rover an equal amount. At one point, Scott succeeded in getting all four wheels of the rover off the lunar surface. He did not detect this, but Irwin made a visual determination. Scott had completed only a portion of the Grand Prix when Irwin realized that the DAC was not working properly, even with a new film magazine. Scott considered putting in a new magazine but then realized that they were under his seat, and it would be too involved to do that and start the Grand Prix over.

"Okay, Dave and Jim, that was a good try," Allen acknowledged. "Let's press on towards Station 9. Let's take a good, clean, comfortable look at that Rille."

Exploring Hadley Rille

On this last EVA, the two astronauts would drive due west toward Hadley Rille, about two kilometers away. With the delays in trying to extract the core tube and getting them separated, they suspected that the traverse up to the North Complex might be eliminated, but Houston had not yet said so. In February 1971, Scott approached Jerry Schaber and asked him about where, if they had an extra hour on the surface, he would he recommend they go to explore? Without hesitation, Schaber said the cluster of craters and hills identified as the North Complex, which Schaber, Mike Carr and Keith Howard believed was an area of lava activity forming a basin. Scott later pushed for inclusion of the North Complex for EVA-3 and both he and Irwin hoped that there would still be time to get to Station 12 and 13 there. As the LRV continued to perform flawlessly, Irwin described their traverse to the Rille, likening it to traveling over sand dunes.

They made their stop at Station 9, short of the Rille, and spent fifteen minutes taking samples and photographs. Scott aligned the antenna so this stop was televised and then, as an experiment, the TV camera was left on while they continued their traverse to Station 9A. Houston received only brief periods of image reception.

"When I mapped the site in stereo for the traverses from the Apollo 14 metric camera pictures," related Schaber, "I found there was a raised lip on the edge of Rille. I told them, 'I have no doubt there is a lip as you go from the proposed LM landing site over to the Rille. You're going to go up slope.' And sure enough, when Dave Scott was on the rover going to the Rille, I heard him say through my earphones that they were going uphill and there was a lip."

The crew made their Station 9A stop at the Rille and Scott once again realigned the antenna. Houston was greeted to spectacular views as Fendell panned the camera around. At this location, Scott gave very detailed descriptions of the far wall of the

Scott photographed on 1 August 1971 during the Station 9 stop on EVA-3. He has parked the rover near the Rille. In the distance rises Hadley Delta, with an elevation of 4,000 meters. (NASA)

Rille and took photographs using the 500 mm lens on his Hasselblad, while Irwin proceeded to take samples. Fendell panned and zoomed the camera with now-practiced ease, to the delight of the scientists in the Backroom. This location proved to be an extremely rich geologic location, and Scott and Irwin knew they would have to spend a considerable amount of time at this station. After completing his series of photos with the large lens, Scott placed it under his seat, fixed the 70 mm lens to the camera, and then went to the back of the rover to retrieve the tongs and the gnomon to perform some sampling of his own. Together, Scott and Irwin ventured down the gradual slope of the Rille and walked down to collect surface rock samples, chipped samples from boulders, core samples and soil samples. They spent nearly an hour at

Station 9A before Allen suggested his crew should move on to Station 10. The astronauts stowed their samples and tools, and then headed northwest, parallel to the Rille, for their next stop.

The Station 10 stop would be a much shorter one, lasting less than fifteen minutes. Here, Scott and Irwin would spend the time taking photos, but no samples. They soon re-boarded the rover and directed themselves back to the ALSEP site to tackle the core tube issue and perform other planned tasks before their departure from Hadley-Apennine. Not knowing how long it would take to break the core tube sections, the decision had been made to bypass the North Complex, to the great disappointment of Jerry Schaber and the others on the science team. Scott and Irwin voiced their disappointment as well, but Houston did not want to push the reserves of the consumables in the Lunar Module and the Command Module by delaying liftoff by one or two orbits in order to get to the North Complex. They wanted the astronauts to liftoff on time. Back at the ALSEP site, the core stems refuse to come apart and Allen later directed Scott to stow this core tube on the floor of the Lunar Module near the Z-27 bulkhead.

Closing out EVA-3

There were two other important tasks to perform that day before liftoff and Fendell made sure his TV camera was properly positioned to record both of them. The first of these tasks was for Scott to perform the first cancellation of a U.S. Postal Service stamp on the Moon.

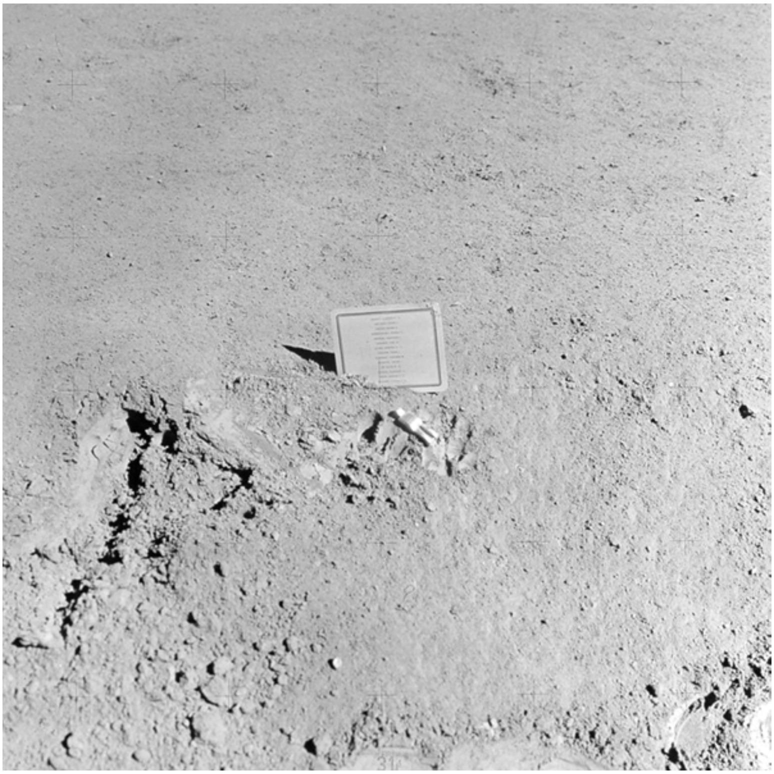
"Okay. To show that our good Postal Service has deliveries any place in the universe, I have the pleasant task of canceling, here on the Moon, the first stamp of a new issue dedicated to commemorate United States' achievements in space. And I'm sure a lot of people have seen pictures of the stamp. I have the first one here on an envelope. At the bottom it says, 'United States in Space, a decade of achievement,' and I'm very proud to have the opportunity here to play postman. I pull out a cancellation device. Cancel this stamp. It says, 'August the second, 1971, first day of issue'."

The second task was actually an experiment conceived by CapCom Joe Allen, who suggested that Scott drop a lunar hammer and a feather to prove that they would hit the lunar surface at the same time. Scott thought the idea was brilliant, and he asked a friend to send him two falcon feathers to take to Hadley. There was time in the schedule for the televised experiment.

"Well, in my left hand, I have a feather; in my right hand, a hammer," Scott said, facing the TV camera. "And I guess one of the reasons we got here today was because of a gentleman named Galileo, a long time ago, who made a rather significant discovery about falling objects in gravity fields. And we thought where would be a better place to confirm his findings than on the Moon."

Fendell zoomed in so everyone viewing could get a close look at the hammer and feather, then zoomed out just as Scott dropped them. The hammer and feather did indeed hit the lunar surface at the same time. Applause could be heard in the Mission Control and the TV clip was played on broadcasts around the world.

Now, Scott and Irwin would soon have to leave their lunar home. After



This small plaque was left on the lunar surface behind LRV-1 to commemorate the astronauts and cosmonauts who gave their lives in the exploration of space. (NASA)

transferring all their samples and film magazines from the rover to the Lunar Module, Scott drove the rover 160 meters from *Falcon* and parked it on a slight rise. He dusted off the LCRU, TV and battery covers, then opened the battery covers. Secretly, Scott performed a touching gesture by placing a small aluminum figure made by Belgian artist Paul van Hoeydonck and a plaque with the names of fallen American astronauts and Soviet cosmonauts on the lunar surface near the rover. He then retrieved a small red-covered Bible from the pocket on his leg and placed it resting against the hand controller. Only then did he align the antenna one last time and after the usual difficulty in doing so, confirmed the picture with Houston after manually lifting the TV camera and pointing it at the LM. The camera had suffered some mechanical difficulties and could no longer be remotely controlled, so Fendell would not be able to tilt the camera up to record the liftoff. Scott took a final color picture of the Lunar Roving Vehicle that had proved so reliable on the Moon and Allen asked Scott to bring back the LRV brush and TV lens brush to the LM for return to Earth. Nothing else was brought back from LRV-1. The last color photo Scott took from the lunar surface was taken through the landing struts of the Lunar Module with the rover in the distance. While Scott had been performing the last

duties at the rover, Irwin had the rare opportunity to do virtually nothing, having done everything he needed to do on his Cuff Check List. So he made several slow trips around the Lunar Module to admire the breathtaking vistas of their landing site before leaving. The crew actually had time to collect more samples, but Houston wanted them back inside the LM to begin their liftoff preparations.

"As the space poet Rhysling would say," Allen announced, referring to the poet in Robert Heinlein's *The Green Hills of Earth*, "We're ready for you to 'come back again to the homes of men on the cool green hills of Earth'."

"Thank you, Joe. We're ready, too, but it's been great. Fabulous place up here," Scott replied.

Scott and Irwin dusted themselves off one last time, made sure they had their samples aboard *Falcon* and then climbed the ladder into the LM. The cabin re-pressurization was completed at 168 hours and 8 minutes GET. Joe Allen told the crew he had enjoyed working on the mission with them and handed over duties to Gerry Griffin, who was joined by astronaut Ed Mitchell. Scott and Irwin spent the next several hours completing the post-EVA activities and preparations for liftoff, which occurred at 171 hours, 37 minutes GET. The astronauts were impressed with how undramatic the liftoff was and how quietly the ascent engine performed. They soon rendezvoused with Al Worden in *Endeavour* and achieved hard dock. Scott and Irwin transferred their precious cargo of samples, the three-section core tube, camera magazines and other items to the Command Module. With full confidence in the Service Propulsion System, they began the sequence to jettison the Lunar Module and send it on a programmed path to impact the lunar surface. The three astronauts would not immediately return to Earth, but would spend several days orbiting the Moon, taking high resolution photos with the mapping camera and launching a sub-satellite that would remain in lunar orbit for many months sending back important data. Eventually, the SPS fired precisely on schedule and the crew of Apollo 15 were on their way home.

RETURN AND SPLASHDOWN

On 6 August, day twelve of the mission, Joe Allen woke the crew and then gave them a detailed news update of the happenings on Earth. Allen also had news about the LRV communications system that had been left on.

"*Endeavour*, this is Houston with a final update concerning the trusty LCRU on the lunar surface. We turned it on yesterday, and it worked beautifully for about thirteen minutes. We ... were panning around, zooming in and out, and got a few more good pictures of the surrounding mountains, and suddenly we lost the TM [telemetry] downlink. In fact, we lost everything in a very short time, about $^{1}/_{60}$ of a second, almost as though someone had turned it off. We waited a while and tried to reactivate it, and did such things as send signals back to it to pan around, while we looked carefully on the passive seismometer for evidence of motion. Apparently it was not responding to the signals. The temperatures were completely normal right before it went off the air. We're not exactly sure what happened."

Shortly after the LCRU update to the crew, Mission Control held an on-board press conference. Questions from the press were posed to the astronauts to get their response regarding their successful mission. One question was put to Jim Irwin by the CapCom: "You described the Lunar Rover as a bucking bronco on the Moon. Would you elaborate and assess the rover's performance and tell us what changes you recommend for the 1972 model?"

"Well," Irwin responded, "there were several times there when we were riding along where we hit a sizable bump and you could see the wheels come off the ground and float through the air [sic], but Dave should comment more as far as the driving. It was really like a bucking bronco, that's true, because I was strapped in. As you know, Dave had to strap me in because I had trouble with my seatbelt, but I really did feel I was on a bucking bronco."

"I think I might add to that," Scott responded. "It's a very stable machine, but because of the $\frac{1}{6}$ gravity, it tends to float. In the simulator we ran in Houston, we saw the same amplitudes, the same degree of bouncing but a different damping. In other words, the vehicle would come off the ground – one wheel normally would come off the ground – and it would take somewhat longer to return to the ground than expected. I think it is just a matter of becoming accustomed to the driving. It's a very stable vehicle. The suspension system is excellent. We had to make some sharp avoidance turns periodically, and in these turns we could tell the vehicle was quite stable – no tendency to turn over whatsoever. I think the only recommendation we really have would be to come up with a new idea on a seatbelt arrangement and we have discussed that also. I think we have some suggestions that we can make when we get back to ensure that you can have both crewmen securely in their seats in a short period of time. Other than that, I think the vehicle is about as optimum as you can build."

The lunar geologic findings from Apollo 15 were considered the most significant of all the missions to date and scientists were eager to examine the core samples, soil and rocks being brought back. Getting a scientist among the last Apollo crews had been a political tug-of-war for several years and Harrison "Jack" Schmitt had finally been selected to be the Lunar Module Pilot on an Apollo mission. A trained geologist – and one who had actually helped to train the astronauts in their lunar missions – was himself now going to go to the Moon. The question was posed to Dave Scott:

> "In view of your comment to geologist Lee Silver about the need for trained scientists on the Moon, do you think scientist-astronaut Jack Schmitt should be included in the crew of Apollo 17, the last of the Apollos?"

"Well, since I really have very little say-so as to which people get selected for which crews," Scott responded carefully, "I might sort of bypass it by the one comment that I think the more qualified a man is on the Moon, the more results you're going to get. I think that's one of the reasons that we put as much time as we did into the geological aspects in the hope of learning enough to bring back some significant data. I think in any situation such as this – any scientific endeavor – you want the most qualified people as possible. You must also remember this is a highly complex operational mission. It requires a great deal of training and skill in order to fly these machines. I think, in particular, Jack Schmitt is a highly qualified individual

in both aspects. And I believe it's up to the management that when they select the crews they select the best people for the flight."

Re-entry and Return to Earth

The crew of Apollo 15 eventually passed beyond the Moon's sphere of gravitational influence and entered that of the Earth. A minor course correction from the Command Module's reaction control jets placed the spacecraft in the center of the re-entry corridor. The crucial Command Module/Service Module separation took place at 294 hours and 43 minutes, Ground Elapsed Time. The capsule was now less than 6,000 kilometers from Earth, traveling at nearly 8,000 meters per second, and accelerating. As the spacecraft entered the Earth's atmosphere, the crew began to see the orange glow put out by the heat shield through the capsule windows as it built up to 5,000 degrees F. As the capsule continued its blistering re-entry into the Earth's atmosphere, the astronauts prepared for the brutal buildup of the gravitational forces on their bodies.

At the completion of EVA-3, Dave Scott drove the LRV several hundred meters away from the LM to permit a good TV image of *Falcon's* liftoff. This was the last photo Scott took standing on the lunar surface. (NASA)

"It is a kind of physical endurance test," Irwin wrote in his memoir, "a traumatic experience, to go from zero-G to almost 7-G during the entry period, during the fireball. For about four minutes you experience this. You have seven times your weight; you weigh over 1,000 pounds. It is physically impossible to lift an arm up to touch a switch, or move a circuit breaker. It was amazing to me that Dave was able to talk to Mission Control while we were coming in. I couldn't take a breath. I was living on the residual oxygen in my lungs. It felt like an elephant was standing on my chest. I couldn't move the diaphragm. It wasn't painful, just a tremendous force on your body."

At 3,000 meters, the drogue chutes deployed, followed by the main chutes. One of the main chutes collapsed, but the capsule could safely make an ocean landing on two chutes without injury to the crew. *Endeavor* splashed down at 295 hours, 11 minutes and 53 seconds GET in the Pacific, within sight of the recovery ship *Okinawa*. The recovery helicopters dropped their swimmers into the water near the capsule to secure the flotation collar around it. Once the capsule door was opened, life vests were passed to the crew to put on. Scott, then Irwin and finally Worden exited the capsule and tumbled into their raft. They were individually hoisted aboard the helicopter using a recovery basket and taken to the carrier *Okinawa*. On the helicopter, the crew was given food and some fresh, clean blue flight suits to put on. As the astronauts got off the helicopter, they were greeted by Dr. Robert Gilruth, Director of the Manned Spacecraft Center in Houston. Gilruth had been head of the MSC for ten years, and this was the first recovery he had personally attended. The astronauts were honored and individually gave short speeches before going below decks as *Okinawa* made for Pearl Harbor. Awaiting the astronauts was a schedule almost as hectic as the mission itself, with debriefings, appearances, meetings, and most of all, family reunions.

At a post-mission press conference, David Scott said, "I think many people have contributed to this pinnacle we've reached. Some have contributed more than others. And we know of fourteen individuals who contributed all they had. Because of that, we left a small memorial on the Moon about thirty feet from Rover one. In a small subtle crater, there's a simple plaque with fourteen names, and those are the names in alphabetical order of all the astronauts and cosmonauts who have died in the pursuit of exploration of space. Near it is a small figure representing a fallen astronaut.

"We went to the Moon as trained observers in order to gather data," Scott said in closing his remarks, "not only with our instruments on board, but with our minds. I would like to quote a statement from Plutarch which I think expresses our feelings since we've come back. 'The mind is not a vessel to be filled, but a fire to be lighted.' Thank you."

Mysterious and unknown Descartes

Capt. John Young banked his T-38 over Patrick Air Force Base and made his approach for landing. He could see the massive Vehicle Assembly Building and the SA-511 Moon rocket standing majestically on Pad 39A at Kennedy Space Center to the north. As Mission Commander, it was still his Saturn V, the Lunar Module *Orion* was still his to land on the Descartes Highlands, and LRV-2 was still his to drive on the Moon. Apollo 16 was still his mission, but it almost didn't happen. In the midst of Apollo's greatest exploratory discoveries, the program in 1972 was in financial and political freefall. Apollo 16, and Apollo 17 that would launch later that year, had suffered a near-death experience in the summer of 1971, brought on by events in 1970.

CUTBACKS IN THE PROGRAM

To meet its 1971 budget of US$3.33 billion proposed to Congress in 1970, NASA would have to cancel Apollo 20, stop production of the Saturn V and related hardware, mothball or close certain facilities and make other agency-wide cuts. Apollo 13 was launched on 11 April 1970 destined for the Fra Mauro Highlands. The catastrophic explosion of one of the cryogenic oxygen tanks in the Service Module fifty-six hours into the flight imperiled the lives of the crew and made Apollo 13 front-page news around the world. Although the crew returned to Earth safely, no Apollo flights took place for the rest of the year while problems with the Service Module were investigated. The failed Apollo 13 mission put further budgetary pressure on NASA.

In September 1970, NASA Administrator Thomas Paine dropped another bombshell. Apollo 15 and 19 would be cancelled and the remaining missions re-designated Apollo 14 through 17. The launch schedule for these remaining missions was stretched from four to six months. Apollo 14 would launch sometime during the first quarter of 1971 with its destination now changed to the one Apollo 13 failed to reach. Apollo 15 would launch during the summer, targeted at the Hadley-Apennine region.

Apollo 16 Commander Capt. John Young gives a classic lunar jump salute for Lunar Module Pilot Charles Duke at their landing site on the Descartes Highlands. (NASA)

Deke Slayton announced the prime and backup crews for Apollo 16 on 3 March 1971. Mission Commander would be veteran Capt. John Young. He had been Pilot on Gemini 3, backup Pilot for Gemini 6, Command Pilot on Gemini 10, backup Command Module Pilot for Apollo 7, Command Module Pilot for Apollo 10, and backup Commander for Apollo 13. He was finally getting his opportunity to command a lunar landing mission.

Slayton selected Charles Duke to be the Lunar Module Pilot. He had been a member of the astronaut support group for Apollo 10 and backup Lunar Module Pilot for Apollo 13, but had never flown in space before. Crew selection was as much a mystery to the astronauts as the initial astronaut selection process itself was to the men who would fly in space. In April 1966, Duke had sat before an astronaut selection committee made up of John Young, Mike Collins, Deke Slayton and Warren North. Duke's undeniable qualifications, coupled with his self-effacing manner, made a favorable impression. He was selected as one of nineteen new astronauts for the Apollo program that year, and three years later was selected for the coveted position of Capsule Communicator (CapCom) for Apollo 11. It was Duke's voice that millions heard as Neil Armstrong and "Buzz" Aldrin brought the *Eagle* to Tranquility Base on 20 July 1969.

"We copy you down, Eagle," Duke radioed to Armstrong and Aldrin seconds after they touched down on the Moon that historic day.

"Houston," Armstrong finally responded, "Tranquility Base here. The Eagle has landed."

"Roger, Tranquility," Duke exhaled. "We copy you on the ground. You've got a bunch of guys about to turn blue. We're breathing again."

As Command Module Pilot of Apollo 16, Slayton chose Ken Mattingly. He, too, was a space rookie and had been among the nineteen astronauts selected in April 1966. Mattingly had been scheduled to fly on Apollo 13, but he had been exposed to German measles and the flight surgeons grounded him, although he never actually suffered from the illness. Slayton gave Mattingly his lunar opportunity on Apollo 16. The backup crew for this mission included Fred Haise as Commander, Stuart Roosa as Command Module Pilot, and Edgar Mitchell as Lunar Module Pilot. They were all veterans of previous Apollo missions.

However, the assault against NASA and its Apollo missions was not over. Despite the resounding success of Apollo 15, the Office of Management and Budget (OMB) proposed to the Nixon administration during the summer of 1971 that the last two Apollo missions, 16 and 17, should also be cancelled and NASA's proposed Space Shuttle program denied. This would effectively mean the end of manned space flight for NASA, which was now fighting for its life. Caspar Weinberger was deputy director of the OMB, however, and he objected vigorously to further cuts at NASA, claiming it would send a message that "... our best years are behind us, that we are turning inward ... and voluntarily starting to give up our superpower status and our desire to maintain world superiority." President Nixon mulled over the implications and sided with Weinberger. Apollo 16 and 17 were saved, and NASA received the green light to proceed with the Space Shuttle.

When the crew of Apollo 15 returned to Earth on 7 August 1971, the debriefings

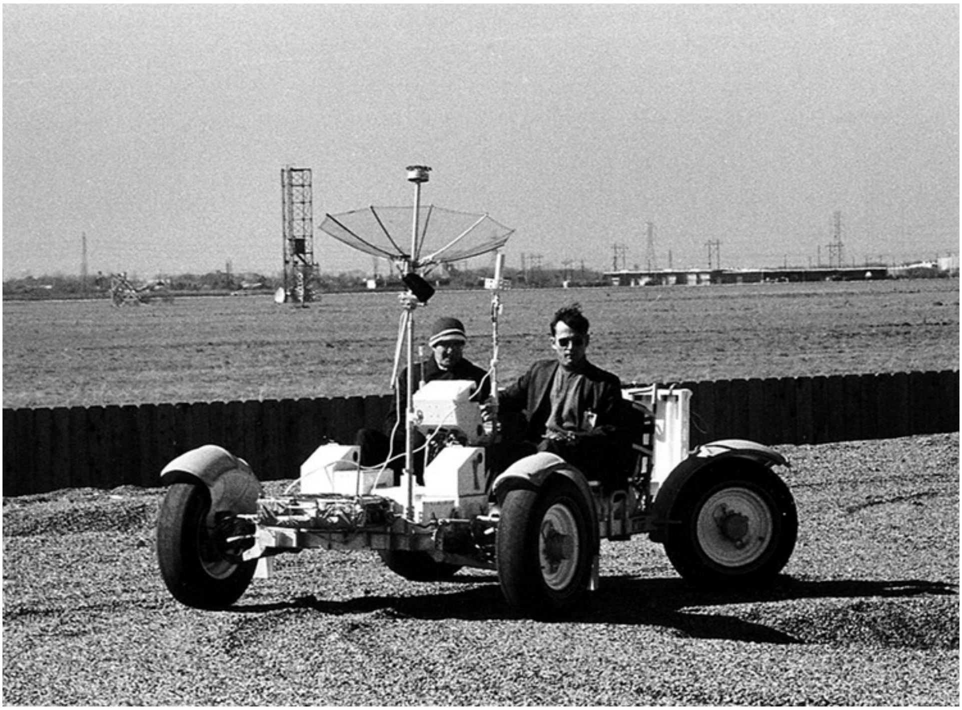
Apollo 16 prime and backup crews study lunar maps and photographs with Dr. Fredrich Horz (left) of NASA's Planetary and Earth Sciences Division within the Geology Branch, and Dr. Stanley Zisk (MIT) at the Manned Spacecraft Center in Houston, Texas. (NASA)

and meetings began, including meetings with the Apollo 16 prime and backup crews. David Scott and Jim Irwin had nothing but glowing reports for the LRV, commenting that the only item they felt needed work based on their experience on the Moon was a minor change to the seatbelts. Both Scott and Irwin emphasized that the seatbelts more than once kept them from ejecting from the vehicle; the design change suggested simply required making the belts more accessible and longer for when the astronauts buckled themselves in.

"We had a big debriefing about Apollo 15," Duke remembered. "One of the things we learned was that the seatbelt was unacceptable, so we changed the seatbelt so it would be easier to buckle and tighten. That was the only change to the rover between Apollo 15 and 16."

LANDING SITE SELECTION, MISSION PLANNING AND PRE-LAUNCH ACTIVITIES

The Apollo Site Selection Board considered two potential landing sites for Apollo 16. The first was Alphonsus Crater, roughly 480 km south of the Moon's center. The second was the Descartes highlands surrounding the Cayley plains. Discussions over



John Young takes the LRV 1-G trainer around the Lunar Topographic Simulation area at the Manned Spacecraft Center. With him is John Omstead of General Electric. (NASA/MSC)

the Apollo 16 landing site took place between March and May of 1971 and, as was usually the case, the scientists and geologists involved in those discussions were not in unanimous agreement over which to select. It was believed, indeed it was hoped by some of the scientists, that Descartes had been volcanic, and was thus an excellent choice for exploration, but the decision was not made any easier due to the failure of the shutter on the Hycon topographic mapping camera flown on Apollo 14 that orbited over the Descartes region.

Dr. William R. Muehlberger was Principal Investigator for the Apollo Field Geology Investigations Team for Apollo 16 and 17. He was assisted by veterans from the USGS, as well as NASA geologists, in the EVA planning for sampling and photography, most of whom had participated in previous lunar surface exploration planning as well as astronaut field geologic training.

"We were supposed to have better photography than we got," Muehlberger confessed in an interview with this author, "but just before the Apollo 14 Command Module went over the Apollo 16 landing site, their big mapping camera failed. So they took a 70 mm Hasselblad and photographed the proposed landing site as best they could. We had a sequence of events based on the photo-interpretation of telescope pictures, which meant we had a resolution of about one kilometer. All

landing sites for Apollo 11 through 16 were picked from telescope geology. They all had other photography to use prior to landing – usually about 20-meter resolution. [The landing site for] Apollo 17 was picked using the high resolution cameras flown on Apollo 15."

Descartes is selected

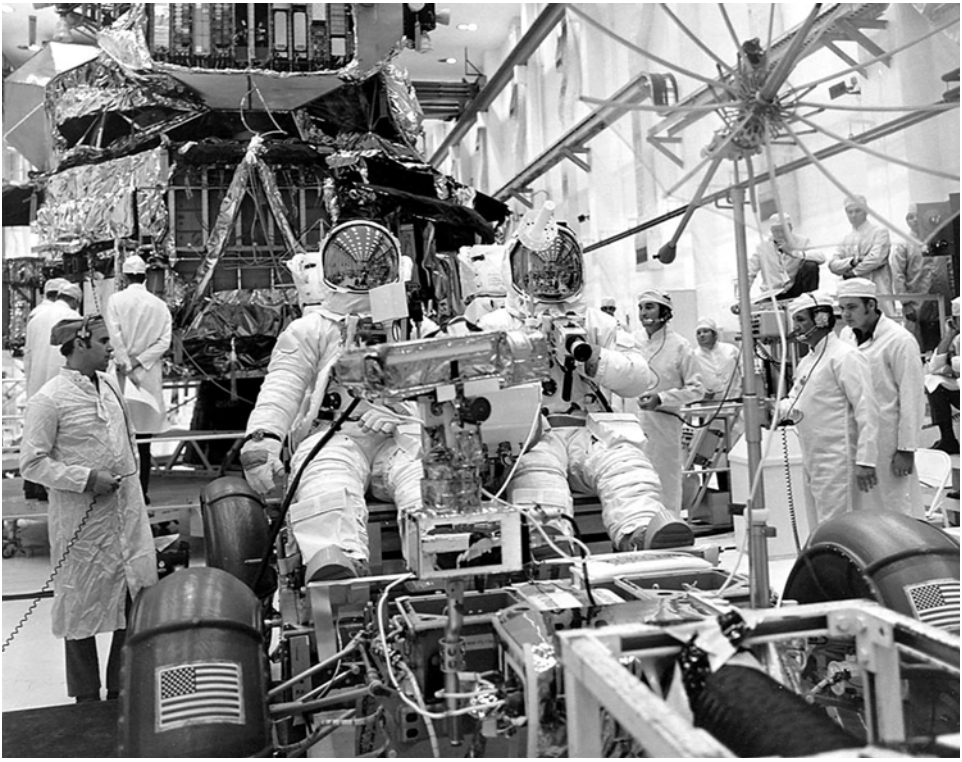
On 3 June 1971, the Apollo Site Selection Board approved Descartes as the landing site for Apollo 16. That decision set into motion a series of events that ranged from mission-specific orbital mechanics and lunar landing simulation planning, to field geologic training and traverse simulations in the Grover for Young and Duke, and much more besides. As with Apollo 15, specific station stops and timelines were established for the Lunar Roving Vehicle traverses and the contingency walking traverses for each of the three EVAs.

The main components of the Saturn V eventually used for SA-511 arrived at the Cape between the summer of 1970 and the fall of 1971. LRV-2 arrived from Boeing on 1 September 1971. After a complete checkout, including crew fit and function tests (as had been done with the crew of Apollo 15), the LRV was folded and stowed on *Orion* in mid-November. The Lunar Module was then secured within the tapered Spacecraft/Lunar Module Adapter. On top of the adapter was then assembled the combined Command and Service Module. This entire assembly was moved to the Vehicle Assembly Building in December. Within the VAB, a crane lifted it more than thirty storeys for it to be attached to the Saturn V's instrument unit. SA-511 was now a complete space vehicle. After several more weeks of checkout, the Saturn V was ready. On 13 December, the crawler-transporter, carrying the Saturn V on the launch platform, left the VAB at its programmed one mile per hour. Weighing a combined 5.7 million kg and towering more than 120 m high, it was the largest and heaviest man-made machine ever to move across the surface of the Earth. It never failed to inspire awe in those who watched it slowly make its way along the crawler way to Launch Complex 39 some 5.6 km away.

Once the Mobile Launch Platform was secured at Pad 39A, several weeks of planned systems integration and testing commenced. However, the failure of a component in the Command Module's Reaction Control System was serious enough to require the entire launch vehicle be returned to the VAB. This and other issues that arose pushed the launch date of Apollo 16 from 17 March back to mid-April. The Apollo 16 prime and backup crews continued their simulator and EVA training and reviews of the mission profile up to the day before the launch.

On 6 April 1972, ten days before the scheduled liftoff of Apollo 16, NASA released the official 176-page Press Kit. It succinctly described the landing site:

> "A hilly region north of the Descartes crater in a highlands area of the southeastern quadrant of the visible face of the Moon is the landing site chosen for Apollo 16. The Descartes site appears to have structural characteristics similar to volcanism sites on Earth, and has two separate volcanic features – Cayley Plains and the Descartes mountains – which will be extensively explored and sampled by the Apollo 16 crew.



John Young and Charles Duke participate in a mission traverse simulation on LRV-2 in the Manned Spacecraft Operations Building at Kennedy Space Center. Tests are also being conducted on their Lunar Module *Orion*. (NASA/KSC)

"The Cayley Plains segment of the landing site is characterized by terrain ranging from smooth to undulating – possibly as a result of fluid volcanic rock flow. The Descartes Mountains, part of the Kant Plateau, are characterized by hilly, furrowed highland plateau material that is thought to have come from a more viscous volcanic flow. Additionally, the Descartes landing site provides an opportunity to study the evolution of young, bright-rayed craters and to extend age-dating to similar craters in other regions of the Moon.

"The landing site has two basic areas which will be explored and sampled: Cayley Plains, including North Ray and South Ray craters; and Stone Mountain and Smoky Mountain of the South and North Descartes Mountains.

"The low crater density in the Cayley Plains suggests an Imbrian age for the rolling, ridged portion of Cayley in the Apollo 16 traverse area. Stone and Smoky mountains, on the other hand, appear to have shapes typical of volcanic formations on Earth – shapes that might be formed by movement of rather viscous material.

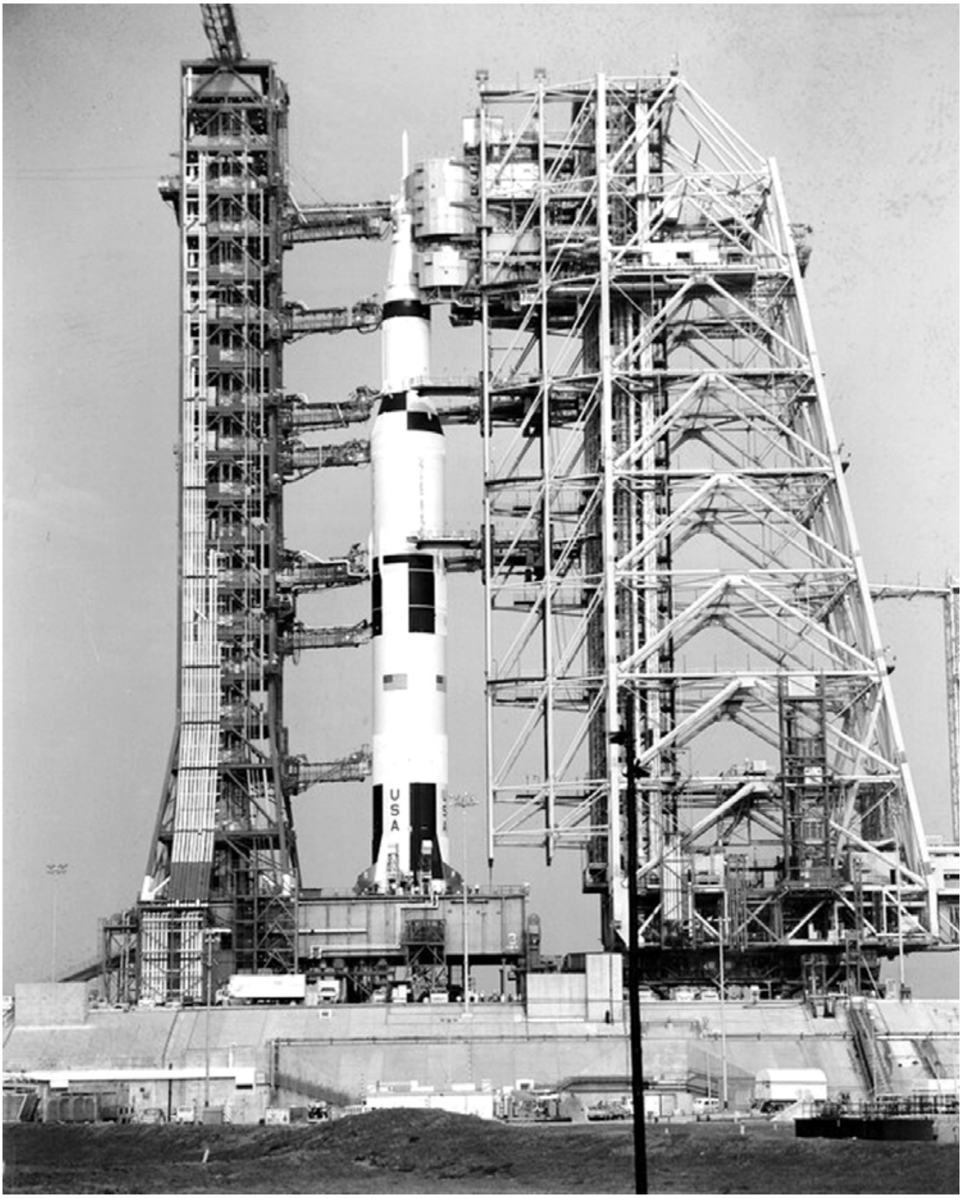
> "North and South Ray craters appear to penetrate deeply into the Cayley formation and reveal the sequence of layering, perhaps through an overlap of both the Cayley and Descartes formations. Smaller, subdued craters in the landing site seem to have a characteristic concave bottom, which suggests that the substrata underlying the crater impact were more resistant than in other crater fields on the Moon."

LAUNCH DAY

At 6:00 a.m. on the morning of 16 April 1972, John Young, Charlie Duke and Ken Mattingly received the knock on their door from the flight surgeon in the crew quarters of the Manned Spacecraft Operations building. It was launch day for Apollo 16. The first order of business was the medical examination, which took half-an-hour. Then it was off to the traditional astronaut breakfast. While the prime and backup crews devoured their steak and eggs, Slayton went over the important milestones for the morning. The prime crew astronauts then went to suit up. At 9:45, John Young, Charles Duke and Ken Mattingly walked from the MSO building to the nearby transfer van, waving to photographers and well-wishers. The weather was perfect for launch, with clear skies, temperature in the mid-80s and virtually no wind.

Once at the pad, the astronauts took the elevator cage up the Launch Umbilical Tower (LUT) to the ninth and last swing arm. Young led his crew across the swing arm to the White Room that enclosed the Command Module. Waiting for them, as with Apollo 15, was Guenter Wendt and his team. Tony England was among the close-out crew and would be the CapCom when Young and Duke were on the lunar surface. Young put down his portable air conditioning unit, and Wendt helped him through the open capsule hatch and into the Commander's couch on the left. Wendt transferred the hose connections from the portable A/C unit to those in the capsule and secured the safety belts. Duke went in next and slid into the couch on the right. Wendt then helped Mattingly into the center couch designated for the Command Module Pilot. Wendt and his crew worked to complete their tasks and close out the Command Module. As he always did, Wendt wished the crew good luck, then closed and locked the hatch. The remaining part of the boost protective cover was secured in place over the hatch and then Wendt and his team left the Launch Umbilical Tower and the pad.

The countdown proceeded smoothly to Apollo 16's liftoff at 12:54 p.m. At engine ignition, Duke's heart rate reached 140 beats per minute, while Young's remained at an amazingly calm 70 beats per minute. With the five F-1 engines at maximum thrust, Duke was startled at the shaking he was experiencing. All the training and briefings had not prepared him for this. Young, meanwhile, a veteran of two Gemini launches and Apollo 10, was unperturbed. Finally, the Saturn V cleared the tower in a matter of seconds. All the F-1 engines burned perfectly until, at just over 2 minutes and 40 seconds, the first stage shut down. The five J-2 engines of the second stage ignited seconds later and the astronauts continued their headlong race toward orbit. At 3 minutes 20 seconds, Young punched the button to jettison the Launch Escape System, or tower, and the CM protective cover. The S-II second stage burned for



The LRV's batteries were installed several days before launch from the Mobile Service Structure (right) through an access panel in the tapered Spacecraft Lunar Module Adapter (SLA). A battery monitor box and cables were installed on a Launch Umbilical Tower (left) service arm to monitor the batteries' condition until launch day. (NASA)

another five minutes, reaching an altitude of 58 km and 112 km downrange, then shut down and dropped away. The S-IVB third stage then fired, putting the crew into their proper orbit. Young, Mattingly and Duke completed one-and-a-half orbits of Earth in preparation for the Trans-Lunar Injection burn. The crew received the welcome "You are go for TLI" message and the single J-2 engine of the third stage fired once more to push the Apollo 16 crew to escape velocity. They were now headed for a place in space where the Moon would be in three days time.

Less than ten minutes after this second and final third-stage burn, the astronauts prepared for Lunar Module extraction. Mattingly performed the command that released the Command and Service Module (CSM) from the Spacecraft Lunar Module Adapter, or SLA. He fired the Service Module thrusters to take it out several hundred feet, turned the spacecraft around and moved back toward the SLA that housed the Lunar Module. With practiced ease, Mattingly docked the Command Module *Casper* with the Lunar Module *Orion*. He then issued the command to release the Lunar Module holding clamps in the SLA and fired the Service Module's thrusters to extract the LM. The S-IVB stage was no longer required and certainly not desired in proximity to the crew's spacecraft, so the crew performed an evasive maneuver to take them a safe distance from the S-IVB stage. Houston then issued a command to the third stage to fire its engine, sending it to impact on the Moon. This planned stage impact occurred before the lunar landing, far removed from the landing site. Seismometers left by the previous Apollo 12, 14 and 15 missions would record the impact.

GO OR NO GO

Young, Duke and Mattingly spent the next three days performing experiments, verifying the functions of the Lunar Module, reviewing mission objectives yet again, and resting. On 19 April, the Moon gave the crew an impressive view out of the Command Module's window and at the precisely planned moment, Mattingly fired the Service Propulsion System engine to slow the spacecraft, allowing the Moon's gravity to capture it as they maneuvered for Lunar Orbit Insertion, or LOI. Four hours later, another SPS burn put the spacecraft into a lower elliptical orbit so that *Orion* would not have to expend as much fuel during landing. This took them as low as 11 km above the surface of the Moon. Young had been here before on Apollo 10, and he relished pointing out the lunar features to his rookie crewmates.

Landing *Orion* would not take place until the following day, so the crew took a well-deserved rest from their labors and caught some much-needed sleep. When their wakeup call came from Houston some eight hours later, the crew prepared for the momentous day. Young and Duke suited up and transferred to the Lunar Module. The Command Module and Lunar Module undocked and Young moved *Orion* away from *Casper* for Mattingly to perform a circularization burn. The two spacecraft flew in a distant formation as they went around the back of the Moon and out of contact with Houston. However, when Mattingly attempted to gimbal the SPS engine using the backup system, the spacecraft began shaking. Alarmed, Mattingly

cancelled the burn and informed Young and Duke. Young told Mattingly that they would hold their formation and wait until they came around from behind the Moon and made radio contact with Houston. All three crewmen were now worried they might have to abort the mission.

When contact was made with CapCom Jim Irwin at Mission Control in Houston, the crew reported the problem with the SPS, saying tersely, "No Circ," for no circularization burn. The red flags went up all over Mission Control. Mattingly was asked to perform the same gimbal commands for both primary and backup systems so they could examine the data. The lunar landing was on hold while mission planners pored over the printouts and conferred with engineers and managers from North American Rockwell, the builders of the Service Module. The hours slipped by, and with them, the hope that *Orion* would land on the plains at Descartes. Finally, the crew received the welcome news from Mission Control that the primary system for the Service Propulsion System would be used without relying on the backup system, and that they were go for landing. However, the prime time television coverage of portions of the mission, highlighted in a cover story in TV Guide magazine, were lost due to this delay. Mattingly performed his circularization burn using the primary system on the SPS on the back side of the Moon and one-half orbit later, Young and Duke began their powered descent.

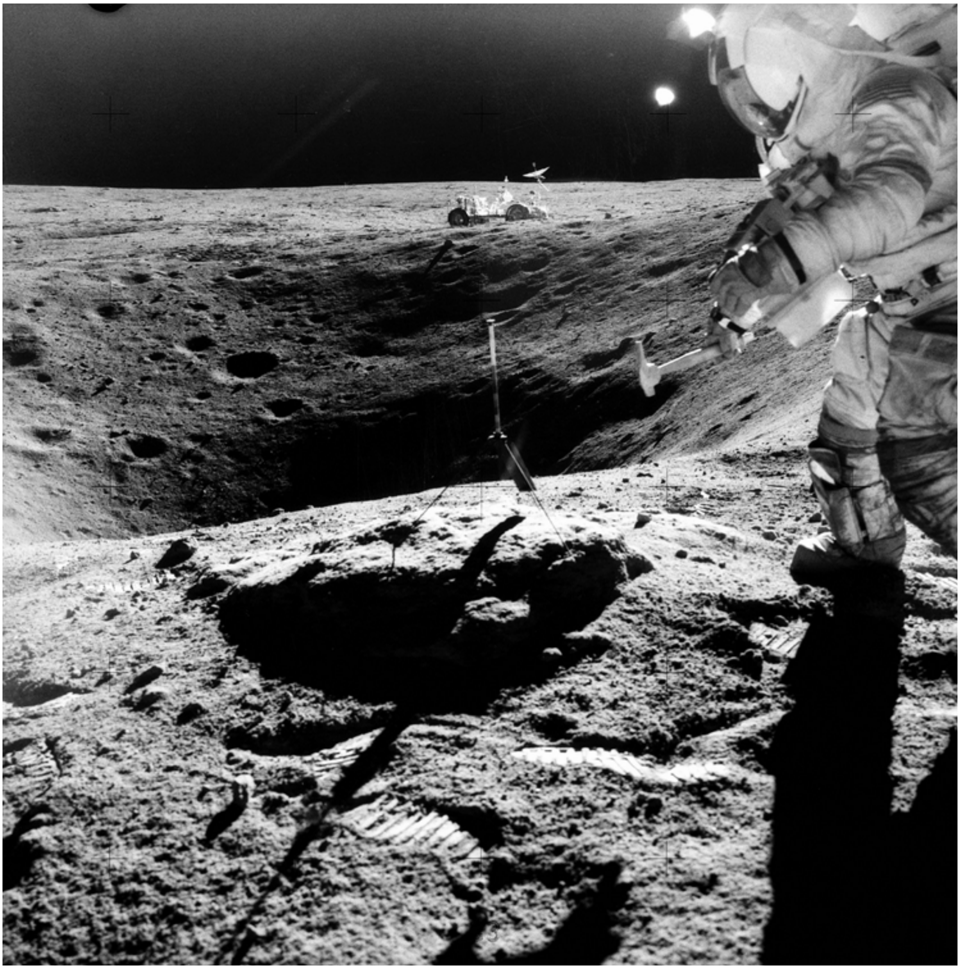
"Our trajectory brought us in face up," Duke remembered in an interview with this author. "We couldn't see the Moon until we got to an altitude of about 7,000 feet, and at that point the LM pitched down and the windows were now facing the Moon so we could see our landing site. There were three major craters in our landing area. The surface around our landing site – to the south and the west – turned out to be fairly rough, with rolling terrain that was cratered with scattered boulders. John took over manual control and by 300 feet, he had picked out a landing spot and hovered over the area like a helicopter, trying to zero out the lateral, forward and aft velocities."

Duke continued to read descent information to Young, barely able to contain his excitement as Young eased *Orion* slowly to the lunar surface. The Lunar Module's long contact probes touched the surface, illuminating the contact light on the LM's control panel. Young counted "One-potato" and hit the engine stop button. The Lunar Module dropped to the surface. In a matter of seconds, the two astronauts performed the steps they needed to secure the LM and check the spacecraft's health in case they had to make an immediate emergency abort and ascent. *Orion* landed on the Descartes highlands on 20 April, 1972, at 140 hours, 29 minutes and 38 seconds Ground Elapsed Time (GET).

Down among the rocks

"Well, we don't have to walk far to pick up rocks, Houston," Young radioed. "We're among 'em!" Young and Duke had successfully navigated through one of the most rugged landing sites encountered during the entire Apollo program, strewn with blocks and countless craters.

"The Descartes region was pervasive in the number of craters it had," Young said in an interview with this author. "We landed, fortunately, in the middle of a big, flat



John Young stands on the rim of Plum Crater during the Station 1 stop, with hammer in hand to break off a sample of the rock in front of him. Young and Duke avoided venturing inside steep-walled craters like Plum. (NASA)

75-meter diameter crater, and landed about as flat as you could land. We landed about three or four meters away from the side of a 10-meter crater. If we had landed in that we would have been in real trouble."

The crew spent the next few hours going through their check list of the Lunar Module, describing the landing site visible through the LM windows to Mission Control, charging up their PLSS, eating, and reviewing their EVA duties for the next day. Due to the extended delay in landing, the crew concurred with Houston that they should get sufficient sleep and make the first EVA the following day. Both astronauts took off and stowed their suits and Young unstowed his hammock, stretched it over the ascent engine cover and attached it to the sides of the instrument panel and the aft

bulkhead. He then unrolled his sleeping bag on top of the hammock and climbed in. Duke stretched his hammock left to right just above the LM floor and placed his sleeping bag on top. One-sixth gravity was a nice change from three days of weightlessness. Too overcome with excitement to get to sleep, Duke took a Seconal sleeping pill. The Lunar Module was not a quiet machine, with valves opening and closing periodically and the cabin heater turning on and off throughout the night. Nevertheless, both astronauts slept well for the next seven hours.

Duke got a rude awakening when Houston dropped the uplink during the communication handover, with a loud blast of static. Duke almost came out of his hammock from a dead sleep. Physicians later confirmed he had pegged the EKG. Young, however, slept through the racket. He got a gentle wakeup call from Duke. Together, they went through the first day's checklist with Mission Control and ate their breakfast. Duke was eager to get going and start their first EVA. After a quick breakfast, both astronauts suited up, and prepared the cabin for depressurization. Young opened the egress door and slowly backed out on his hands and knees. On the porch of the lander, he lowered necessary equipment to the lunar surface, and then pulled the pin that released the upper chassis of the LRV. He then went down the ladder to the lunar surface.

"There you are, mysterious and unknown Descartes . . . Highland Plains," Young said, surveying the landing area. "Apollo 16 is gonna change your image." One of the first things Young did after stepping onto lunar firma was to reach down and pick up a rock to verify the ease of mobility in the pressurized EVA suit. Duke followed his Commander down the ladder several minutes later and together, the two astronauts prepared to deploy the Rover.

"At that point we started pulling on the lanyards for the pulleys to deploy the rover," recalled Duke. "That whole sequence probably took no longer than fifteen minutes. Then we continued lowering it to the surface. Once the rear wheels were on the surface, we had to release the pins for the front chassis, then put it on the surface and check the locking pins. Then, we picked it up and walked out with it and turned it around so John could drive it off. We then mounted the TV and movie cameras, various antennas, put the geological experiments on the back, raised the seats, and checked it out. The next three to four hours were involved with placing the Apollo Lunar Surface Experiments Package (ALSEP) near the landing site, planting the United States flag and taking photos. After that, we climbed into the Rover and our objective was a place called Plum Crater, about a mile west of our landing site. We aligned our navigation system and off we went."

EVA-1: TO PLUM AND BUSTER CRATERS

Although Young had managed to pick the rock up off the lunar surface without too much difficulty, this was their first experience of getting into the rover's seats in $\frac{1}{6}$ G. As David Scott and Jim Irwin had told them during the debriefings, the stiffness of the pressure suit on the Moon made getting into and out of the rover seats somewhat difficult. A certain technique was required to accomplish this.

Charles Duke works beside the Lunar Rover at Station 4 during EVA-2 near Stone Mountain, 22 April 1972. Young has parked the rover on a small plateau overlooking Cayley Plain in the distance. Note the size of the blocks Young had to drive over. (NASA)

"Getting into the rover in 1-G was easier than up on the Moon," Duke explained. "Down here you had the weight of the backpack that made it easier to bend the suit. Up on the Moon, the way I found to get into the rover was to reach over and hold onto one of the antenna posts, bend my knees as much as I could, then jump up and pull hard to get into the seat. The suit was so stiff you couldn't just sit down on the seat and then swing your legs in. It just didn't work that way."

The astronauts soon discovered that the EVA would be slow-going in the LRV, due to the many impact craters and other obstructions that lay along their path. Young was concerned about what these obstructions might do to the rover.

"There were block fields that would rise from these new craters," Young related. "What I was worried about while driving the rover at Descartes was that we would run across one of these block fields and take out the suspension system. We were very careful in going around all the blocks with the rover. Fortunately, it had Ackerman [front and rear] steering, so it could turn within its own length. It was very

maneuverable. It did exactly what we wanted it to in terms of getting us around fast and to places we could never have gotten to walking.''

During their first EVA, Young and Duke had followed a procedure of driving out to the furthest destination and then working their way back toward the LM, in the unlikely event the rover had a breakdown and they found themselves having to walk back. Thus, they could never travel further in the rover than the limits of oxygen and water in the Personal Life Support System (PLSS) would allow. They set their course for Plum Crater and a much larger crater nearby identified as Flag Crater. Their traverse took them past Buster Crater on the right, Spook Crater on the left and then the small Halfway Crater on the right, with Plum and Flag Crater dead ahead. Young estimated the diameter of Buster at 45 m and Spook at more than 300 m. Duke observed large boulders in the bottom of Buster Crater. They stopped at the rim of each crater and took photos and samples before finally reaching the relatively small Plum Crater on their left. Flag was estimated to be over 120 m in diameter. Positive identification proved difficult at first, due to overshooting their landing site by several hundred meters, and having the low angle of the Sun at their backs, known as zero phase. This created considerable concern for Young. While he could make out the blocks and avoid the larger ones, the craters were nearly impossible to see. After thorough discussions with Dave Scott who drove the rover on Apollo 15, Young voiced concerns about having to drive the first traverse at Descartes in the zero phase condition. But it was unavoidable at that time on the lunar surface and in the direction they had to drive to get to their ultimate destination, Flag Crater. Young drove cautiously at 4 to 5 kph.

''Driving down-sun in zero phase is murder,'' Young admitted to CapCom Tony England.

''It is, isn't it?'' Duke responded honestly.

''It's really bad,'' Young emphasized.

Young and Duke made their Station 1 stop at Plum Crater and began their photography and sample collection.

''We found out real quick that we couldn't match the craters on our maps with the ones on the surface,'' Duke told this author. ''We finally found Plum Crater, spending about an hour there. Then we drove back to the vicinity of the experiments package. I got off the rover with the movie camera and John did what we call the Grand Prix, which gave the engineers an idea of what the Rover looked like as it bounced across the Moon. That was the only movie clip from the Apollo missions of the full rover under way. The rest of the time, we had the movie camera mounted on the rover. You could see yourself driving and bouncing across the Moon but you couldn't see the operation of the whole vehicle.

''During the training and actual mission, ''Duke continued, ''John was the driver and my job was to navigate and be what I call the travel guide. While we were under way, we couldn't have the TV picture on because the High-Gain Antenna was not stabilized and could not always point at the Earth. When we were driving, I kept a running commentary going to Mission Control and the science teams about what we were seeing. We didn't feel on the lunar surface that the rover would ever present us with a life-threatening situation, but it was 'squirrelly'. The steering was sensitive.

We would be sitting there, bouncing along, and my elbow would hit John's elbow, which would cause him to move the T-handle, and the rover would tend to fishtail. It was like driving on ice with rear-wheel drive. We actually spun out one time, but even then it never felt like it was going to turn over.''

The largest rock sample ever collected

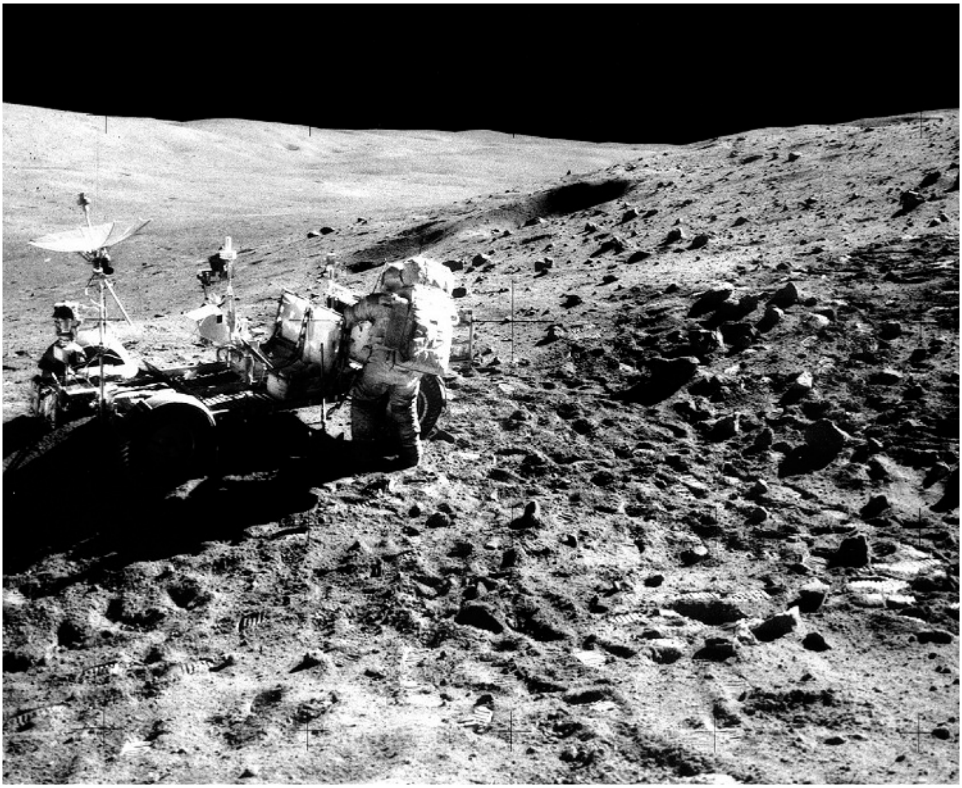
They completed their Station 1 stop at Plum and their sample collection included the largest rock sample ever collected on any Apollo lunar mission. At the urging of CapCom Tony England, Duke was asked to pick up a rock so big that Duke was incredulous. He knew England was being urged by Bill Muehlberger to collect the rock, which was right on the lip of Plum with its steeply sloped walls. With the stiff suit, Duke had difficulty bending down to pick up the 11.7 kg brute, resorting to trying to roll it up his leg, only to drop it again. Duke let his feelings be known to Mission Control.

``If I fall into Plum Crater getting this rock, Muehlberger has had it,'' Duke fumed.

``We agree,'' England admitted.

The decision to collect that sample was not Muehlberger's alone, but was a consensus of the geologists in the science Backroom. There were more than two dozen scientists actively involved in lunar surface exploration activities as the EVAs were being conducted. It was an impressive array of individuals who formed a scientific and geologic brains trust, participating in the greatest feat of exploration ever conducted. Jim Lovell was the science coordinator who kept the needs and interests of the astronauts on the lunar surface foremost in mind. Muehlberger had Gordon Swann and Dale Jackson working with him while Young and Duke relayed to Houston what they saw and what they were doing and, conversely, what Muehlberger and his team wanted the astronauts to investigate. This is where the LRV's TV camera and audio feed were so vital in conducting the science on the Moon. Robert Sutton would write down on index cards the information on each rock that was being described and kept them cataloged according to type. Tim Hait operated an overhead projector with transparencies that he feverishly wrote on with the information the astronauts were describing, which was projected on the wall so that others could see and refer to it later. Lee Silver sat nearby, taking it all in and seeing how well the astronauts conveyed their observations. Scattered around the room were the other key participants, all of whom had a stake in this extraordinary moment in time. In another room down the hall from the science Backroom, there was a team carefully photo-documenting what was being beamed to Earth.

``As soon as the crew stopped and got off at some point, and adjusted the TV antenna so the TV would work,'' Muehlberger said, ``Ed Fendell in Mission Control would do a 360-degree pan with the TV camera on the rover. We had a crew who were taking Polaroid pictures of that and they were sticking them together right there to make a panorama. The geologists on that team would circle features that we wanted to look at when there was time. The panorama was brought up with interesting objects circled within minutes of when the TV camera had relayed the scene to Earth. Then, when the astronauts were doing something that didn't need the



Station 4 from a different angle in this photo taken by Duke. Both astronauts were amazed at the LRV's hill-climbing capability. Caley Plain below was far from being flat. (NASA)

TV camera on them, I would relay up to Ed to pan or zoom up on a particular rock, for example. Then, the geologists would bring up the photos with whatever had caught their eye. Those were brought up and set in front of me within minutes of taking them. I had plenty of time then to look at them, to comment and to send them instructions, via the CapCom, that they might want to add to the information they had on their Cuff Check List."

This was exactly what happened when the geologists spotted the large rock they wanted Duke to pick up. They thought, with its large crystals of plagioclase, that it was a white-clast breccia with a gray matrix. It was a sample they definitely wanted to examine on Earth. Duke finally succeeding in getting it up to his waist, and after examining it, admitted it had beautiful crystals. This sample would later be nicknamed "Big Muley." Duke stored it under his seat on the LRV.

Then they climbed aboard the rover, buckled up and set off for their Station 2 stop. Young turned the rover around and headed for Spook Crater and nearby Buster Crater. After they stopped, Young did some LRV housekeeping by dusting off the LCRU and the TV camera lens, and then realigned the High-Gain Antenna.

England asked Young to proceed with setting up the Lunar Personal Magnetometer (LPM), while Duke took photographs of Stone Mountain and South Ray Crater with the 500 mm lens. Duke then went over to Buster Crater, and commented that it had a pronounced slope up to the rim, with interior walls that dropped off steeply. He took rock and soil samples at Buster. Their tasks at Station 2 completed, Young and Duke then drove back to *Orion*. Young relied on the LRV navigation system going back, as he had driving out, and it was already proving itself indispensable in the harsh lunar Sun-lit conditions. Both astronauts were pleased with the rover's performance.

"Man, this is a fun ride," Duke remarked to Houston. "Okay, Tony, we're doing ten clicks."

"Outstanding," England responded

"Occasionally, the back end breaks loose, but there's no problem," reported Duke. "This is *really* some machine."

The second Lunar Grand Prix

Back at the LM, Duke got off and took the 16 mm Data Acquisition Camera from the rover in preparation for Young to perform the planned lunar Grand Prix. After the problems that plagued the 16 mm DAC on Apollo 15, the camera had received modifications to resolve the problems and prevent their occurrence on Apollo 16. Duke walked about fifty meters away and once he told Young the camera was rolling, Young began the test with a hard acceleration. Almost immediately, the LRV began rocking fore and aft in response to going in and out of small craters at 10 kph.

"He's got about two wheels on the ground," Duke commented to Houston. "There's a big rooster tail out of all four wheels and as he turns, he skids. The back end breaks loose just like on snow. Come on back, John. And the DAC is running. Man, I'll tell you, Indy's never seen a driver like this. Okay, when he hits the craters and starts bouncing is when he gets his rooster tail. He makes sharp turns. Hey, that was a good stop. Those wheels just locked."

Young made another run for Duke to film. The original plan was to get four or five minutes' worth of film of the Grand Prix, but England felt that the two runs Duke had described would give NASA, Boeing and GM all the information they wanted, so the test was cut short. Young then armed the mortar package and Duke deployed the Solar Wind Composition Experiment. Duke then reported the relevant LRV navigation readouts, battery and motor temperatures to England in Houston. With the samples they had collected and described to the geologists through their communications, it was slowly becoming evident that Descartes had not experienced recent volcanism, as had been strongly believed.

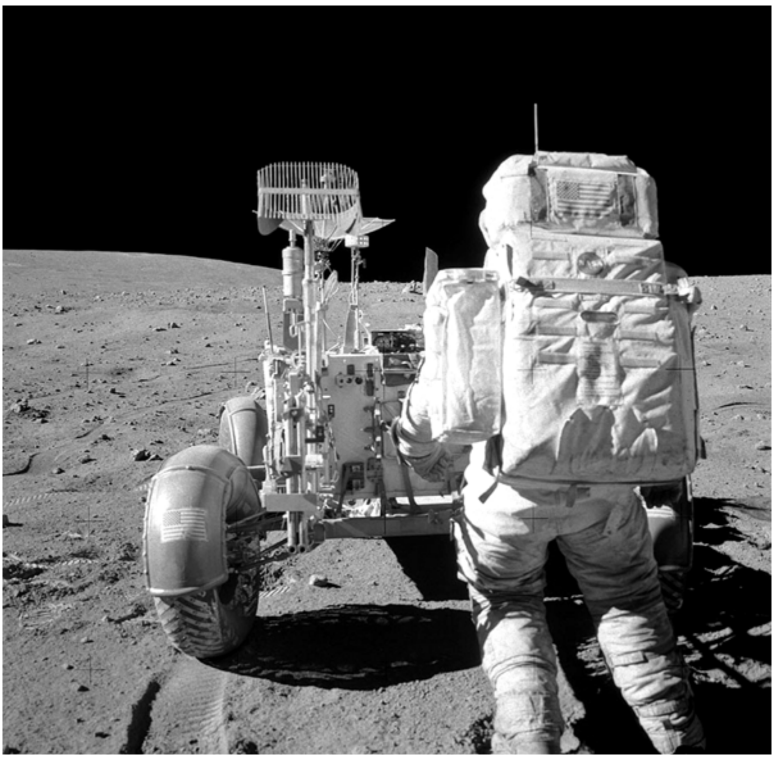
"My general impression of this thing is [that] I'm a lot more surprised at how really beat up this place is," Young admitted. "It must be the oldest stuff around, because it's just craters on top of craters on top of craters. I mean, there's some really big old subdued craters that we don't even have mapped on our photo map, I'm sure of it."

Young opened the LCRU covers to sixty-five per cent. They placed Big Muley

near the MESA until the end of their mission. With the rest of the EVA-1 samples safely in the Sample Return Containers, they did their best to dust themselves off and then the two astronauts re-entered *Orion*. They had been on the surface for seven hours during their first EVA. It had been a good first day, except for the loss of the heat flow experiment when Young inadvertently broke the connecting cable with his foot. When they re-pressurized the cabin and took off their helmets, the pungent odor of lunar soil could be smelled. They helped each other get out of their suits, cleaned themselves up as best they could, ate their evening meal, and continued a running dialog with Houston regarding the accomplishments of the day.

EVA-2: SOUTH TO STONE MOUNTAIN

On Day 2, Young and Duke would spend the majority of their EVA in the vicinity of Stone Mountain, some four kilometers south of *Orion*. The day before, Young had said Apollo 16 would change Descartes' image, but the Descartes Highlands had surprises of a different sort in store. The astronauts suited up and exited the LM,



John Young works at the rear of the rover during EVA-2. The Lunar Hand Tool Carrier is in the open position. Note the sample rake. Both the high-gain antenna and the low-gain antenna are pointed almost directly up, towards Earth. (NASA)

then prepped the rover, loaded the film canisters in their Hasselblads, got on the rover and initialized the navigation system, and then headed off.

Each stop during the EVAs was identified with a station number. They had visited three stations the previous day, so the first stop this time was Station 4 at Stone Mountain. Here, they would really be able to put the rover through its paces and see what it was actually capable of. The rover was going to go mountain climbing, and the NASA and Boeing engineers were listening intently as Duke and Young reached the base of Stone Mountain and looked up. They would take the rover as far up as they could, find a suitable place to park, and take samples and photos.

"The Rover could climb a 25-degree slope," said Duke during the interview. "We climbed Stone Mountain, which was to the south, on the second day. That was the steepest slope, and we were about 300 to 400 feet up from the Cayley Plains at the highest point." The astronauts had a commanding view of the valley and could even see *Orion* four kilometers away. Young was impressed that the rover had made such a steep climb so effortlessly, and said so to Houston.

"If anyone had told me this thing could go up the side of that mountain ..." Young added ...

"I wouldn't have believed it," Duke interjected. "This is a real beauty."

"We climbed a steeper-than-20-degree hill," Young remembered during the interview, thinking back, "because we bottomed out the rover and broke off the pitch indicator. I was really surprised when I looked down Stone Mountain. I wondered how we got up a slope that steep."

Young found a small plateau where he could park the rover for their Station 4 stop. The antenna was aligned and CapCom Tony England happily remarked that Houston had a picture. Ed Fendell went into action doing a complete pan from that location. Duke took 500 mm photos and noted to England that the rover's right rear wheel was off the ground, an indication of just how rugged their parking position was. The slope of Stone Mountain was littered with blocks, as was visible to those watching in Houston. Both Moon walkers gave detailed descriptions of their samples and general observations, spending an hour on their tasks at Station 4. When they finished the sample collection and photos, they strapped themselves in and prepared to go back down. Duke attempted to start the DAC, but once again, the camera would not work. Had it worked properly, it would have made interesting viewing as the astronauts headed down Stone Mountain. The men felt like they were going to fall out of the front of the rover, but for their seatbelts.

"Okay. Okay, we're going down-slope ... cross-slope, Tony," Duke commented, "and I feel like I'm about to fall out."

They made stops at Station 5 and 6 further down Stone Mountain, but already they could observe from the samples they collected that Descartes had not experienced the volcanic activity they and the scientists on Earth had surmised. The block samples they collected proved that they were part of ejecta from meteor impacts, not from volcanoes. This was confirmed when the samples were examined later.

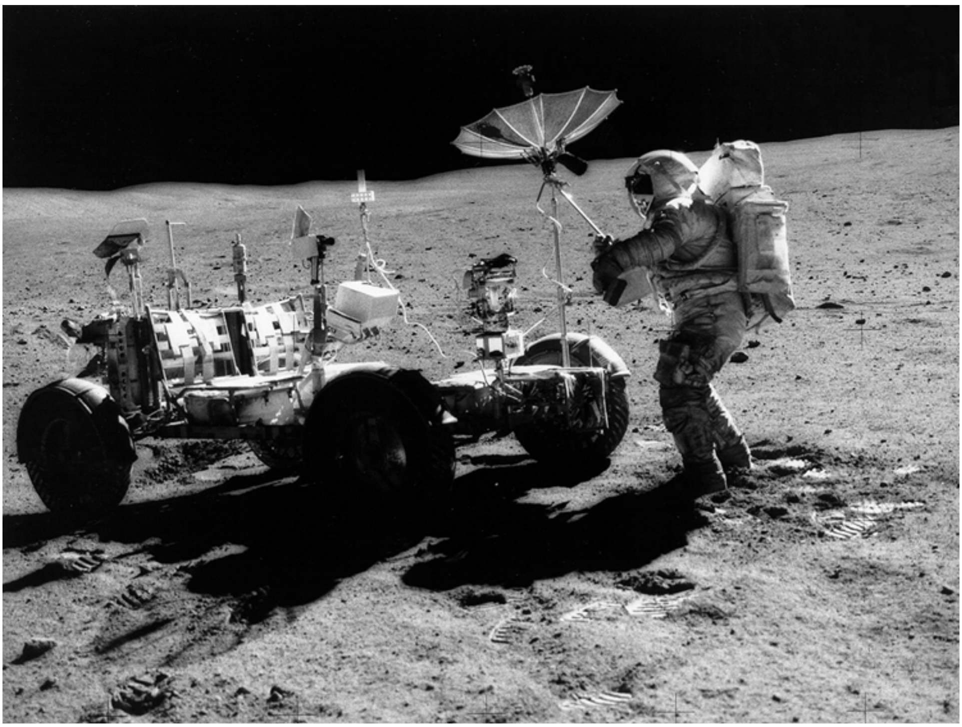
"At our site," Young stated, "they predicted we'd find rille-like volcanic rocks and there were none. They were all anorthosites and anorthositic breccias. That's a

totally different kind of rock. We found rocks at our site that were age-dated between 4.2 and 4.5 billion years old."

As they continued their EVA that day, the two marveled at the stark beauty of the Descartes Highlands against the deep blackness of space. All the astronauts on the Apollo lunar landing missions spoke of this and sometimes the words failed them. How do you describe the indescribable? All their training had not prepared them for this. However, they would all be moved by their experiences on the Moon, in ways both religious and psychological. They were on the Moon in a sliver of time among billions of years.

Losing the fender extension

Houston eliminated the Station 7 stop, so Young and Duke completed their stops at Stations 8, 9 and 10, which included Stubby Crater, rays from South Ray Crater and other parts of the Cayley Plains. Their stop at Station 8 was given one hour and with five minutes remaining, Young was finishing with Duke's sample collection bag while at the rear of the rover. Young turned to go around the back of the rover and his leg caught on the right rear fender extension, tearing it from its guide rails. The fender extension fell to the lunar surface.



Young adjusts the high-gain antenna after stopping at Station 8 during EVA-2. Both Young and Duke exclaimed about the spectacular beauty of the Decartes region where they landed. (NASA)

"There goes the fender," Young informed Houston.

The wheel was now exposed to nearly the 11:00 o'clock position. This would result in lunar soil being thrown up and forward while underway. Tony England informed Young and Duke that their time was nearly up and they had to prepare to leave for Station 9. Duke mentioned the fender damage.

"We lost a fender, Tony," Duke said. "The pusher-downer fender on the right rear wheel is gone."

"Roger. Just like the trainer," England said matter-of-factly, referring to the damaged fenders that the 1-G trainer experienced. Young, apparently, made no attempt to retrieve the fender extension to see if it could be reinstalled. The Boeing and GM teams in Houston immediately took note of this, and the thermal control engineers knew that it would aggravate dust accumulation and therefore heat dissipation from the TV camera, batteries and LCRU, not to mention dust raining down on the astronauts themselves as they drove. The astronauts climbed onto the rover, buckled up and proceeded to Station 9. They made no remarks about possible dust being thrown up. As they looked back up Stone Mountain, the two men were amazed at the rover's climbing ability.

"Tony, I bet you that rover would have climbed right on up to the top of Stone," Duke said to Tony England at Mission Control in Houston.

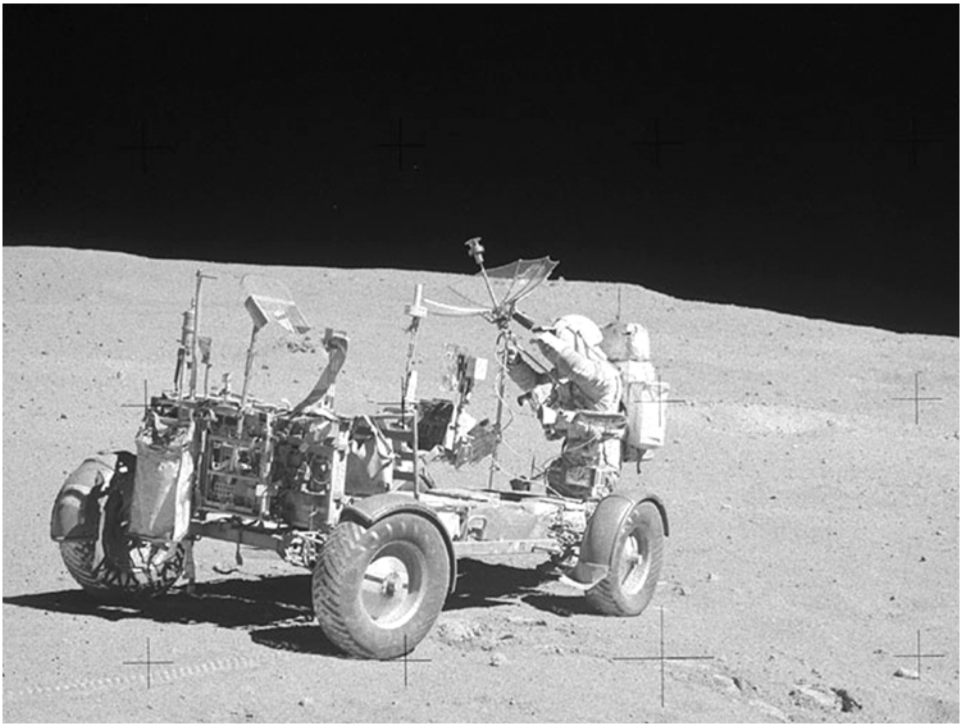
"Sure it would," Young concurred.

"This is some machine, I'll tell you'," Duke exclaimed. During training at KSC, Young and Duke were advised to practice slowly and carefully approaching rocks so that undisturbed soil samples could be collected and the rocks photographed without soil being kicked up onto them by their boots. The astronauts were amused by this advice and described the procedure as "sneaking up on a rock." This was very important to the geologists in the Backroom in Houston, but Duke and Young couldn't help having fun with it. As Young slowly walked up to a rock at their Station 9 stop, Duke told CapCom Tony England to be quiet while they proceeded to sneak up on the rock. Unfortunately, Fendell did not know which direction they had gone and was unsuccessfully trying to find them. Fendell was shaking his head as he panned the camera, when he finally found them.

"The first Great Lunar Rock Hunt and we missed it," England said, expressing disappointment. The geologists had wanted to see how Young and Duke approached the sample site, though Duke had been careful to photo-document Young's sampling effort. Knowing the TV camera was finally on the two of them, Duke gladly demonstrated Young's approach.

"Tony, John was sneaking just like this," Duke said, mimicking Young's motions. "He really got up to it ... It didn't even know he was coming."

There were smiles all around Mission Control and in the science Backroom. It was a rare moment of levity during the mission of Apollo 16. The surface of the Moon is totally unforgiving, and the risk of an equipment failure vital to the astronauts' survival was an ever-present danger. The SPS anomaly and the failure of the circularization burn to take place as planned still had Houston nervous, and Apollo 13 was not far from everyone's mind. But for now, the mission was going well and Young and Duke were in high spirits. They spent thirty-five minutes finishing



During EVA-3, the right rear fender extension of the LRV was broken and torn from its extension rails, visible in this photo taken by Duke of Young at Station 13. Resulting lunar dust on the battery covers increased battery operating temperatures as MSFC had warned. (NASA)

their sample collection and taking photographs. As they got on the rover, England informed Young that Battery 2 was warm, and advised configuring the circuit breakers to draw power only from Battery 1. Both front and rear steering were active though. Young and Duke kept up a running commentary with England about the sights along their return traverse, with Young remarking that Cayley Plain was anything but a plain, being in fact quite an undulating surface with countless blocks he had to constantly try to avoid. Duke remarked that he had spotted a crater that reminded him of a sinkhole crater he and England had seen in Kapoho, Hawaii, on one of the geology training sessions. England asked Duke to swing the DAC around to film it, but Duke admitted he did not have the strength in his hands to reach out and move it. Duke then suggested to Young a novel approach to photograph the crater.

"Let John turn over that way and as he swings around, I'll give you a couple of pictures of it. Can you make a 360, John?" Young agreed, and suddenly realized what they were accomplishing.

"That would be a neat way to take a pan, Charlie," Young said.

"That's just what I'm doing, taking a pan of that thing. Okay, we got it!" Duke stated with obvious satisfaction.

"Okay," Young affirmed.

"Great. We got a pan from the rover, Tony, with a 360," Duke finished. They continued their trek back to the LM.

"Sure is comforting to be able to hear those old wheels turning," Young told England. "You can hear them; they make a rumble."

"We can't hear them, but we can imagine it's comforting," England admitted.

Lunar dust problems

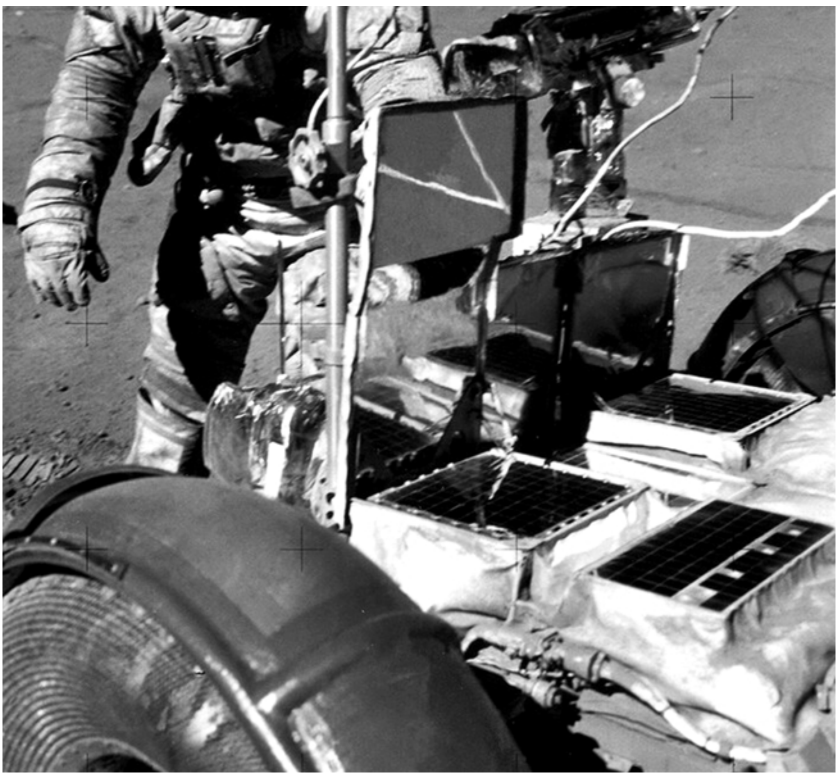
"A walking traverse in this place would be terrible," Duke admitted. The missing fender extension was having the expected, if undesirable, effect of tossing lunar soil over them and their vehicle.

"We've got to get over this ridge, John, and we'll see the old LM," Duke assured Young. "Man, I am covered from head to foot with dust. Boy, those fenders really are useful, Tony. This one we lost in the back has resulted in us being ..."

"Pretty dirty," Young finished.

"...a Double Pig-Pen," Duke said.

"We're going to have to really brush," Young acknowledged.



Young photographed Duke near the front of the LRV at the end of EVA-3. Both battery covers are open and the radiators are clearly visible. (NASA)

"Charlie, you mean you guys are getting dirty?" England asked, realizing the consequence of the missing fender segment.

"Maybe that's how we'll get our extension," Young ventured, hoping the extra time required to dust themselves and the rover off before they re-entered the LM would qualify them for the EVA duration record. They arrived back at the ALSEP site in just under twenty-five minutes, having covered 2.6 km, and England instructed them to perform their Station 10 Cuff Check List tasks. Young and Duke then put pressure on England for a ten-minute extension. The decision really rested with the Flight Surgeon, who wanted to make sure the astronauts got their full allotment of sleep.

"Why don't you just give us an extension?" Young asked England.

"Tony, how about an extension, you guys? We're feeling good," Duke echoed.

"Oh, we understand and we can understand why you wouldn't want to get back in," England replied, "but we'd like you to get back in on time. And you've got a lot of science there, so don't worry about it."

"You said all we would do tonight is sit around and talk!" Young remarked, obviously perturbed. Young had a point. Getting as many varied samples as possible was more important to him than talking about the day's activities, but it would also give them more time on the lunar surface and maybe set an EVA record in the process. It was then that Young made a discovery that startled him. As if by some miracle, he found that one of his sample collection bags had fallen from his PLSS and had wedged between the left rear fender and the LRV frame. Young identified it as bag number four. This would have proved a significant scientific loss had it dropped to the surface during the traverse with no time to retrieve it. Tony England had still not received approval to give Young and Duke the extra time they wanted and the seconds ticked by as the astronauts waited for a decision.

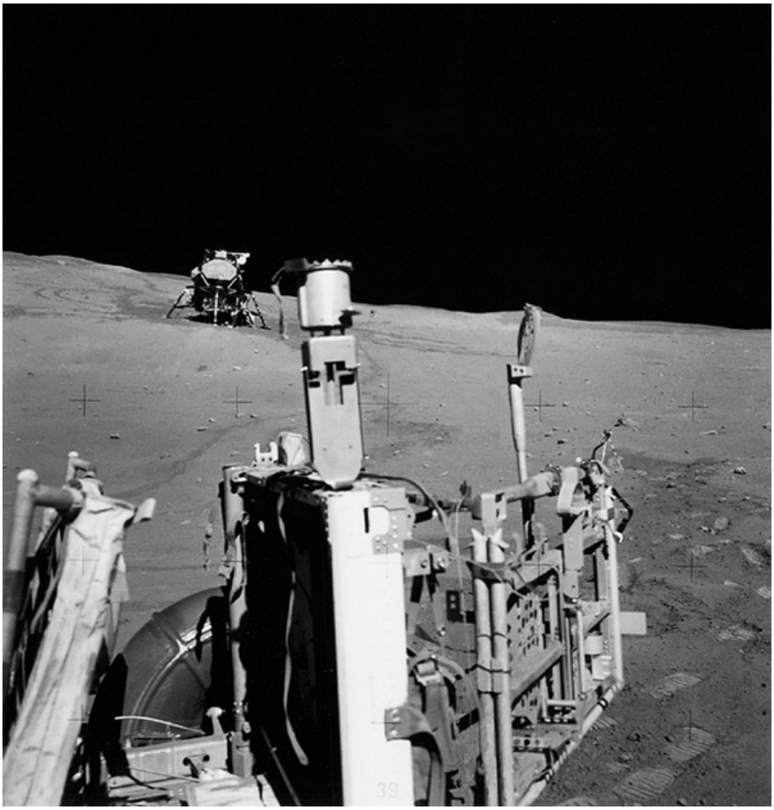
"Okay, we'll go ahead and give you ten minutes," England finally responded. Duke then went ahead with driving in his double core sample, but he encountered resistance. Young offered to take over that duty so that Duke could perform the penetrometer duties. When they had completed this and had taken additional photographs, Duke walked back to the LM and Young went over to the LRV to perform some switch configuration changes sent to him by England.

"Okay. Except for the PWM Select and the Drive Enables, we would like everything back to nominal," England instructed. "Circuit breakers in, and drive power on Bus Delta, steering on Bus Delta ... That's rear steering."

"Circuit breakers are in, drive power's on Delta, and steering's on Delta," Young responded.

"Good show. And we understand you reset [the navigation] before you came," inquired England.

"Yeah, I did that," Young answered before getting on the rover and driving back to the Lunar Module. Duke put the various samples and the core tubes into a rock box and they continued their EVA closeout activities, including dusting off the LRV's battery covers and the LCRU radiators. Duke made sure that the rock box and sample collection bags were safely aboard the ascent stage. On this second day, they had traveled over 11 km in the rover. By the time Young closed the LM hatch



John Young took this photo of the LRV's final parking position at the end of EVA-3 on 23 April 1972. (NASA)

and began re-pressurization, they had broken the EVA record set on Apollo 15. This was an important personal milestone for Young and Duke, knowing that their third and last EVA the next day would be their shortest on the Moon.

As they took off their helmets and gloves, Duke remarked that the lunar soil smelled like gunpowder. This was a comment shared by most of the moonwalkers and the odor was quite strong as the lunar soil became exposed to oxygen for the first time in billions of years. They had been back inside for about twenty minutes when Tony England handed over CapCom duties to Ed Mitchell.

"Ed, how are you doing today?" Duke asked.

"Pretty good, Charlie. And it went real great. We're real pleased down here."

"We're happy as a clam," Duke responded. "We just had a great time, having fun as well as the work."

"You know, Ed," Young interjected, "when we got up on top of that mountain and I'd been driving up it all the way. When I turned around and looked down, I thought, man, you've just nearly bit off more than you can chew here."

Indeed, the drive up Stone Mountain was perhaps the most memorable event of a

very full day of exploration. "Spectacular" was a word Duke had used numerous times that day to describe the vista from Station 4. Young was also moved by the stark beauty of the Descartes Highlands. In the 1989 book *Footprints* [Acropolis Books, New York], authors Douglas MacKinnon and Joseph Baldanza interviewed all twelve Apollo Moonwalkers. Young was asked what was the most vivid impression he had of being on the Moon, and he answered, "The Descartes landing site is one of the most dazzlingly beautiful regions on the Moon. The view from Stone Mountain has got to rank as being one of the most truly beautiful views that's ever been seen by a human being. It's quite a place. I think we ought to go back as soon as we can, because there's so little we know about it."

EVA-3: NORTH RAY CRATER, HOUSE ROCK AND SHADOW ROCK

When the landing was delayed by six hours, NASA had seriously considered canceling the third and last EVA. Muehlberger became alarmed, because almost a third of the anticipated science would be lost if this occurred. Geologist Dallas Peck was asked to put together a tiger team to write a report to convince NASA of the importance of retaining the third EVA. The report was effective and in the end, NASA chose only to reduce the EVA by two hours. Still, Young and Duke's third day on the Moon would be no less rewarding and challenging than the first two. While loading the rover, Young had nothing but admiration for the LRV. It had proven utterly reliable, capable of climbing the steepest slopes he dared, had shrugged off the unforgiving lunar landscape with its countless blocks that pounded the suspension and wheels and had continued to perform flawlessly. After outfitting the rover with the needed equipment and initializing the navigation system, the astronauts strapped themselves in and headed north.

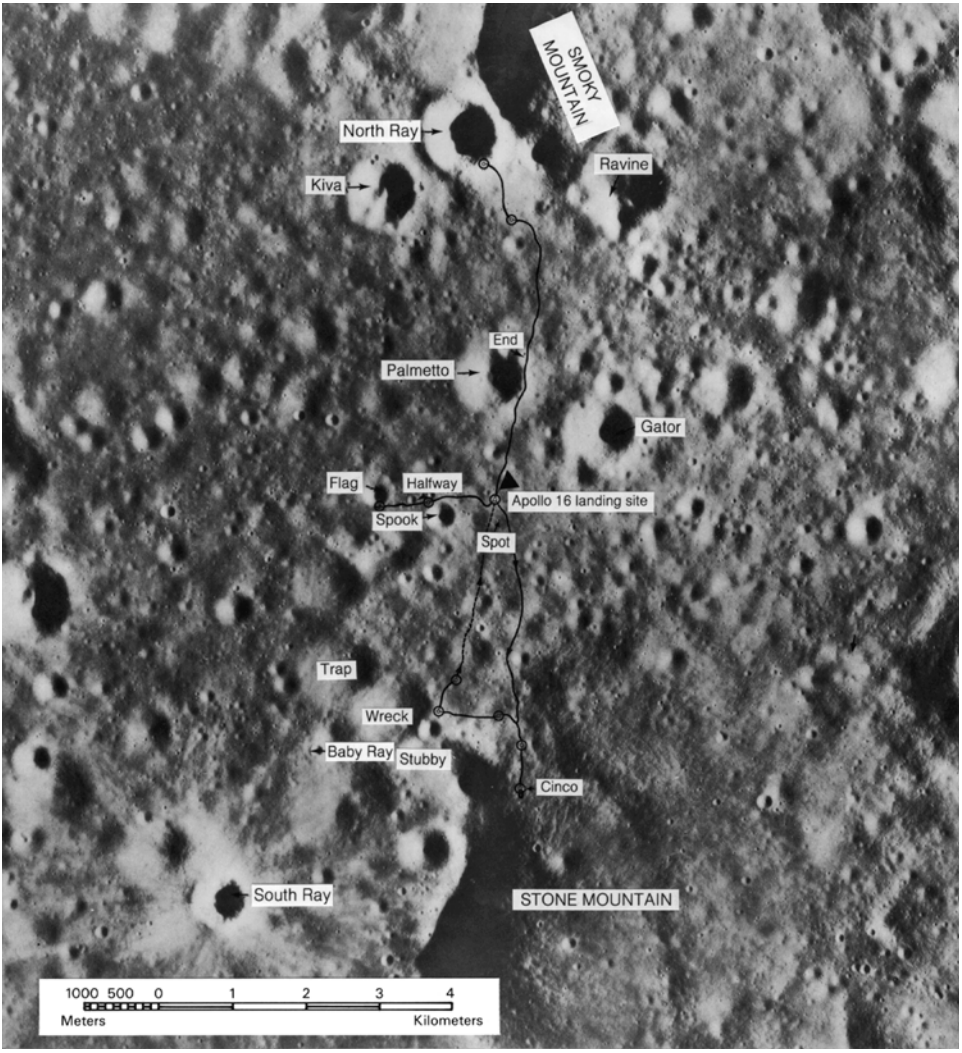
"One of the most significant places we went to was on the third day up to North Ray Crater, which was four to four-and-half miles away," said Duke. "There were some significant geological areas up there. We found House Rock – a huge boulder. Looking across North Ray Crater, you could see layering in an out-cropping of rock. The Rover just extended the radius of operations ten to fifteen times."

Young and Duke were headed toward some of the biggest craters at Descartes. They would pass Palmetto Crater on their left, which was estimated at 800 m in diameter. Duke kept up a continual dialog of his observations with Tony England, and was impressed with how subdued the craters were regardless of size. They finally arrived at North Ray Crater, which was roughly 900 m in diameter and more than 200 m deep. This would be Station 11. Young once more aligned the TV antenna for Houston, then walked over to the rim of North Ray. Much of the crater was strewn with large boulders and the surrounding area was littered with similar boulders and blocks.

"Man, does this thing have steep walls," Young remarked, standing on the crater's rim.

"They said 60 degrees," Duke added.

"I can't see to the bottom of it, and I'm just as close to the edge as I'm going to



The Lunar Roving Vehicle helped Young and Duke to traverse more than 26 kilometers of the Moon's surface at Descartes and collect more than 95 kilograms of lunar samples. (NASA)

get. That's the truth,'' Young confessed. England instructed Duke to take a series of photos of the interior of the crater, shots of Smoky Mountain, and stereo photos. Young performed a pan of the site with his camera. The most significant boulder at this station stop was a massive black boulder that dominated the lunar surface. Ed Fendell was taking in all he could with the TV and the geologists in the science Backroom were enthralled.

''That was virtually the only big boulder we could see in the photographs that we

had before the mission,'' Muehlberger stated. ''We knew that big boulder was up there but when you've got pictures that are no better than 20-meter resolution, you don't have a lot of chance to go and pick out specific things for the astronauts to go and sample. Well, on that traverse, Young and Duke got to the rim of the crater they thought House Rock was near, but it turned out to be a long walk. They were running up against the constraints of their air supply and having to get back, get buttoned in, and get launched. They took a nice panorama of the inside of the crater. They would have liked to have walked closer to the rim of North Ray Crater, but they didn't know how steep it was going to be and therefore it might be a one-way trip if they fell into the crater.''

It's further away than you think

After completing their photography and sample collection along the rim of North Ray Crater and the vicinity near the rover, including several sizable white boulders. Young and Duke then set their sights on the massive boulder in the distance. But on the Moon, distances were very hard to gauge. The absence of familiar objects often seen on Earth made it very deceiving in trying to estimate either the size of surface features or the distance to them. This phenomenon was about to play itself out again in their trek toward the boulder. House Rock, as it was named, was a spectacular geologic find. It was indeed as big as a house, measuring roughly 12 m high and 25 m long. It had been a portion of the lunar crust blown free during the meteor impact that created North Ray Crater millions of years before.

''Okay, Charlie. Let's go back to the Rover. Put your bag [sample collection bag] on there and head out for the big rock. Because you got a bag on your back, and we'll use it.''

''Look at the size of that biggie!'' remarked Duke.

''It is a biggie, isn't it,'' Young acknowledged. ''It may be further away than we think because ...''

''No, it's not very far. It was just right beyond you,'' Duke said confidently.

''Theoretically, huh?'' Young replied, doubtful.

''Yeah.''

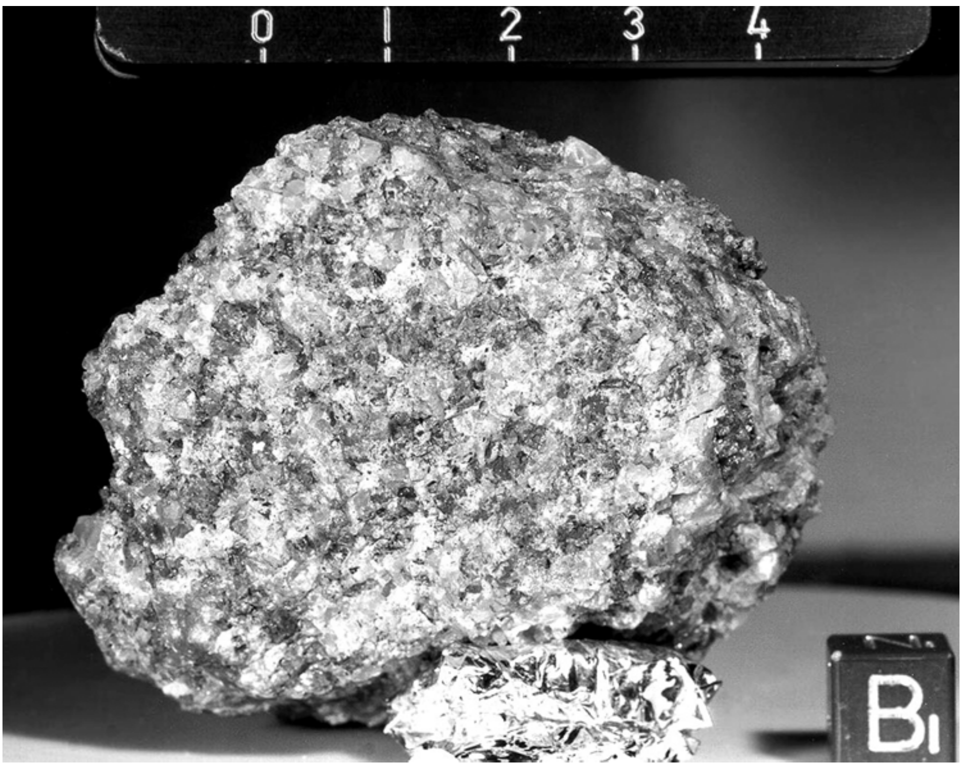
''Like everything else around here, a couple of weeks later ...'' Young replied sarcastically.

He had a suspicion that the big boulder was a lot further away than it appeared. They grabbed their sample collection tools and bags and began their sample collection at various locations close to and far from the rover. Ed Fendell panned and zoomed the TV camera, following the astronauts brilliantly. They appeared to sink into the lunar surface because they were moving down a shallow crater. In another rare moment of humor recorded on film in the science Backroom, Jack Schmitt, watching the TV image on the screen quipped, ''And as our crew sinks slowly in the west, we bid a fond adieu ...'' Everyone in the room laughed.

As they reached House Rock, Young described the boulder's composition based on his visual observation. England informed them that they had seventeen minutes before the wheels of the rover had to roll again. Sadly, the two astronauts were so

intrigued as they walked toward House Rock that neither of them stopped long enough to take good photos of it in its entirety. Duke did take pans once they got closer, and these photos were later pieced together to create a composite of the boulder's base. The face of House Rock proved intimidating to sample, so they knocked some samples from a nearby smaller boulder and took soil samples around the base of House Rock itself. All too soon, England informed them that they had to head back to the rover. When they reached it, Duke spotted that the battery temperature warning flag for Battery 2 had popped up on top of the rover's Control and Display Console. This would occur any time the battery temperature exceeded 125 degrees F. He looked at the battery temperature gauge and reported 135 degrees and Houston instructed them to configure power to be drawn from Battery 1 before driving off. After stowing their samples and tools, they buckled themselves in. Bypassing Station 12, they drove on to Station 13. On this traverse, the rover once again proved its mettle.

"Look at that slope!" Duke enthused. "Be sure that you got the brakes on. Tony, this is at least a 15-degree slope we're going down, and that rover came right up it and you never even knew it. Brake that beauty, John. Man, are we



Among the lunar samples the LRV helped John Young and Charlie Duke to collect was this troctollite, an igneous rock composed of olivine and plagioclast. (NASA)

accelerating. Super. I should have had the camera pointed forward. Okay, Tony, I think it was 179 at 4.4, that little steep slope there. Whoever said this was the Cayley Plain?"

"Well, that was down the rim of the crater here," Young explained to England. "We've just set a new world's speed record, Houston; seventeen kilometers an hour on the Moon."

After driving for eight minutes, Duke and Young arrived at their designated Station 13 stop. The missing rear fender extension resulted in excessive lunar soil being deposited on both the LRV and the astronauts themselves. England informed them that the LCRU was heating up and Duke remarked that the rover needed serious dusting. Young aligned the antenna while Duke took a complete photographic pan of that station stop. There were numerous intriguing boulders at this stop, and one in particular they named Shadow Rock for its pronounced overhang. They once again took samples of the soil, rake samples, broke off several pieces from Shadow Rock, and took soil from the shadowed portion of the boulder. They spent a half-hour at this station, then had to head back to the LM and a final station stop near Station 10, identified by England as Station 10 Prime, roughly 50 m northwest of Station 10.

As they approached the small End Crater northwest of Palmetto, Young drove the rover in a tight circle for Duke to take a 360-degree photographic pan. They proceeded to the ALSEP site and then parked the rover. Duke gave England the rover's Control Display Console readings. A rake sample was first taken by Duke, followed by a double core sample. They finished taking their last samples prior to closing out EVA-3 and Young then drove the rover 100 m east of *Orion* and parked it for observation of the LM liftoff.

"Okay, Houston. I'm parked on a slope of about 10 degrees – or 5 or 6 or 7 degrees [down-slope] toward the Lunar Module, and it's my guess that this will help your cooling some, because it [the LCRU radiator] is looking towards deep space a little. I'm about 100 yards [90 meters] directly aft of the Lunar Module. Is that where you want this contraption to be?"

"Okay. It's heading 165," England reported. As it turned out, Young had actually parked the rover about twenty meters short of the proper location necessary to permit Ed Fendell to elevate the TV camera in sequence with the rise of the ascent stage of *Orion* during liftoff. This would not become evident until the actual event. The closeout decal on the rover remained obscured by dust even after brushing, so Young asked England to read it off to him. Young performed the necessary tasks to prepare the rover at its final resting place and England asked that the front end of the LRV be dusted. Duke joined Young at the rover to brush off the dust-covered LCRU, the battery covers and the TV lens when he was able, and the LRV radiator dust covers were opened for the last time. Young and Duke had less than an hour left on the lunar surface and worked quickly to complete their necessary tasks and make sure all their samples and film canisters were aboard the spacecraft. There were no momentous words as first Duke then Young climbed *Orion's* ladder, crawled inside and initiated cabin re-pressurization. England reported that they had conducted a 5 hour 40 minute EVA, with a hearty congratulations from the science Backroom. The

astronauts had collected 96 kg of rock and soil samples, England informed them, which was over their limit for liftoff, so Houston was deciding whether some of that weight would have to be ditched. Duke quickly informed Houston that they had thrown out the Constant Wear Garments, the sleep restraints and anything else that could be left on the lunar surface that did not have to go with them that morning. This seemed to convince Houston that they could keep all the samples they had, including "Big Muley." Jim Irwin took over as CapCom. Apollo 16 was about to leave its lunar base.

LEAVING DESCARTES FOR HOME

At 171 hours and 31 minutes GET, an explosive charge fired a steel blade through the four-inch thick bundle of cables that joined the two stages electrically. More charges severed the bolts holding the stages together, and the ascent stage fired. The rover's TV camera, controlled from Houston, panned upward as it followed the ascent stage until it was out of range. Then the camera panned slowly down to the descent stage left behind. The unnerving realization hit those watching the monitor in Mission Control that the Moon was once again totally lifeless. There was only a machine – the rover's TV camera – that showed signs of movement, surveying the Descartes Highlands that had been home to Apollo 16.

Young and Duke soon rendezvoused with Mattingly, who had orbited overhead performing numerous experiments and taking hundreds of photographs with the Service Module's mapping camera while they were on the Moon. There were smiles and handshakes as the crew was reunited and they spent another day in orbit resting and getting ready for their return home. The SPS burn was critical to break them free of the Moon's gravity and send them towards Earth, and it worked flawlessly. On the crew's trip back to Earth, a news conference was held that included a TV transmission. Questions posed by reporters in Houston were read by Hank Hartsfield in Mission Control to Young, Duke and Mattingly. There were sixteen questions for the crew of Apollo 16, the last of which asked if they had any recommendations for the crew of Apollo 17. Young answered for all of them by saying that the Apollo 17 crew should enjoy it as they had, and then went on to thank all those who had supported their mission. Then, Young elaborated on the discoveries of their mission and the man after whom the region of the Moon they had visited was named.

"Well, let me just say one thing, Hank," Young responded. "Mr. Descartes said it . . . 'There is nothing so far removed from us as to be beyond our reach, or so hidden that we cannot discover it.' You know, Descartes was a French mathematician and philosopher for whom the region was named and I guess, really, the story of our mission so far is we've been out testing this theory. My personal assessment of where we are right now is that as soon as we get the rocks back in the LRL [Lunar Receiving Laboratory], we'll be making headway toward proving he was right."

John Young examines one of the lunar samples he collected at Descartes at NASA's Lunar Sample Receiving Laboratory. (NASA)

A safe return

On 27 April, the Command Module *Casper* re-entered the Earth's atmosphere traveling at more than 16,000 kph. A picture-perfect splashdown marked the end of the greatest adventure in the lives of John Young, Charlie Duke and Ken Mattingly. Helicopters from the *USS Ticonderoga* picked up the crew and then the capsule. It was a mission all three men realized they could not surpass. The helicopter landed on the carrier, steps were rolled up to the side and the three astronauts exited and saluted. It was another lunar triumph for the United States.

After introductory comments by the ship's Admiral and a prayer from the carrier's chaplain, John Young stepped up to the microphone and thanked four pivotal groups of people who had contributed to Apollo 16's success. First, he thanked his crew for their professionalism, skill and courage. Next, he thanked the dedicated people at the Manned Spacecraft Center in Houston, Texas and those around the United States that supported the Apollo 16 mission.

"The third group of people that nobody ever talks about very much is the American taxpayer," Young continued. "I think you taxpayers – we taxpayers – you got your money's worth on this one. You really did. You saw an example of goal-

oriented teamwork in action. The kind of thing that made this country great, and the kind of thing that's going to keep it that way. You also saw – and it's sitting right there in *Casper* right now – a mission of discovery. There are secrets in that vehicle that nobody knows. There's some basic knowledge and understanding in that vehicle right now. We're going to find those things out, and one of these days it's going to benefit us all, I can guarantee you. I feel that if we hadn't done our mission, we'd have been remiss in not uncovering this basic knowledge. And what I'm saying is that the basic knowledge that's locked in those secrets is pushing back the last real frontier – the frontier of the unknown. And by golly, that's essential to the survival of humanity on this planet.

"And the fourth group of people," Young concluded, "and maybe the people I feel more at home with than anybody, is the good old U.S. Navy."

The history of the Moon was literally being re-written. Descartes had proved that. The Preliminary Science Report for Apollo 16 revealed that the Descartes region had not been what had been assumed prior to the mission. Nearly ten years of sample analysis was reviewed for the definitive account of the discoveries made there, for *Geological Survey Professional Paper 1048* written by George E. Ulrich, Carroll Ann Hodges and William R. Muehlberger and published in 1981. In the Summary of Geologic Results, the authors wrote, in part:

> *Several hypotheses have been proposed to explain the origin of the terra plains and the hilly and furrowed terra, both of which are non-volcanic according to evidence from the Apollo 16 mission. Orbital and surface results of the mission, together with post-mission photo-geologic investigations, suggest that ejecta from the Imbrium basin constitutes a major part of both plains and mountains at this site.*

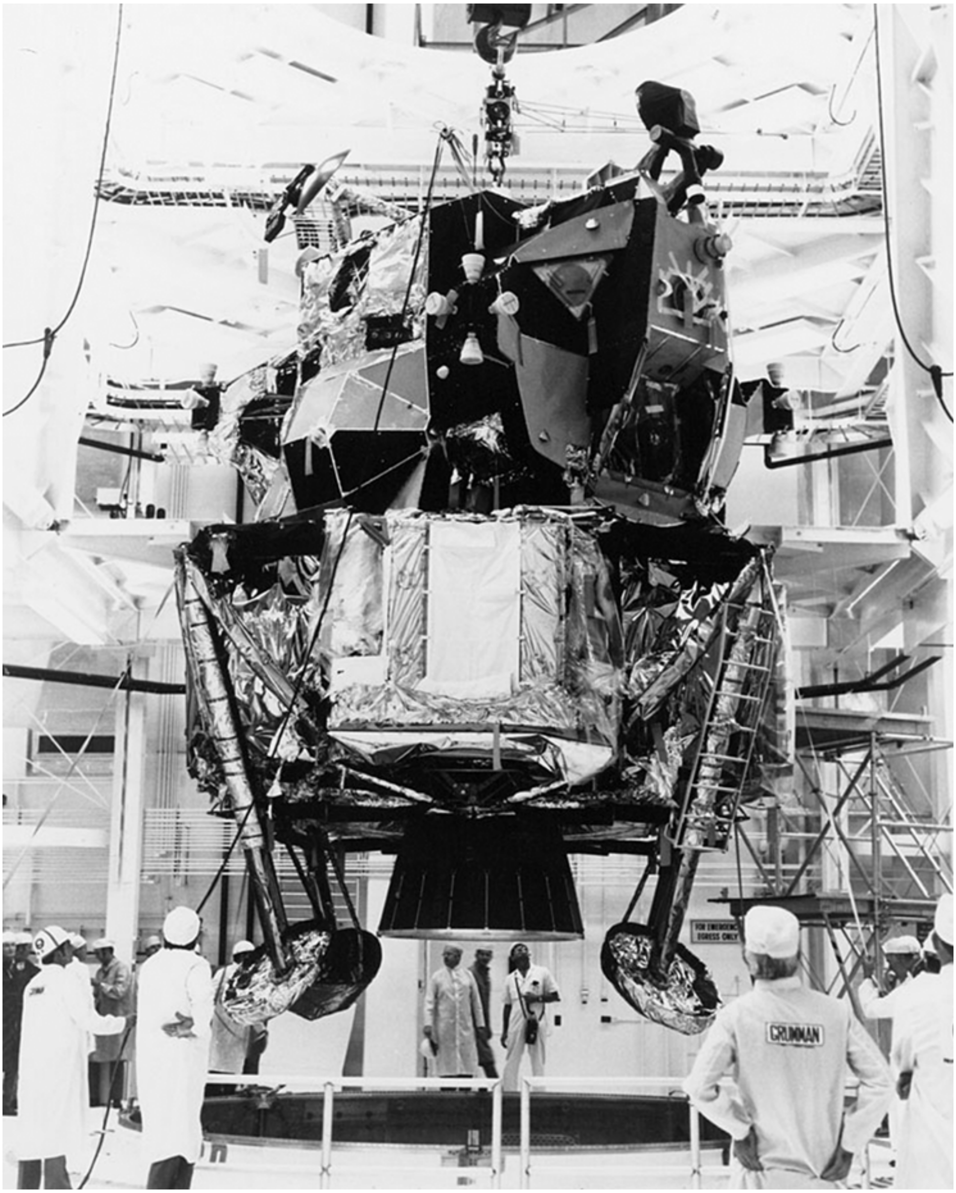
The Lunar Roving Vehicle had contributed tremendously to the manned lunar exploration to establish the true origins of the Descartes Highlands. Only one more mission remained in the Apollo program before the era of exploring the Moon in the twentieth century would come to a close.

Destiny at Taurus-Littrow

On 21 May 1969, the crew of Apollo 10 entered their circularized orbit of 113.9 km by 109.1 km around the Moon after two Service Propulsion System burns. Aboard the Command Module (CM) *Charlie Brown* were mission Commander Thomas P. Stafford, CM Pilot John Young and Lunar Module (LM) Pilot Eugene Cernan. This mission was the first "all up" test of the Apollo spacecraft system that would eventually land on the Moon, including the Lunar Module. The stated mission of Apollo 10 was to "demonstrate crew, space vehicle and mission support facilities during a manned lunar mission and to evaluate LM performance in cislunar and lunar environment." It was designed to duplicate every event of the historic Apollo 11 landing, except the landing itself. On 22 May, Stafford and Cernan entered the Lunar Module *Snoopy*, which then separated from the Command Module and prepared to descend to 14 km above the lunar surface. In a critical phase just prior to firing the ascent stage after separating from the descent stage, an incorrectly set navigation system switch triggered the Reaction Control System (RCS) into trying to compensate, causing the Lunar Module to tumble out of control.

"Gimbal lock!" Stafford barked. This would result in the loss of the navigation platform and was potentially catastrophic. They fought to regain control of the spacecraft, even as it spun and jerked from the mixed signals fed by the navigation radar to the RCS, and together they brought the LM under control. They proceeded with the ascent stage firing and Stafford and Cernan successfully rendezvoused with John Young in the CM. It had been a heart-stopping moment, but one that experienced pilots and astronauts like Stafford and Cernan were equipped to handle. They had averted a disaster that could have sent the Lunar Module crashing into the surface of the Moon, killing the crew and dashing America's goal of landing men on the Moon and returning them safely to Earth. Their cool thinking and fast responses saved the mission. Apollo 10 achieved all its goals and kept America on track for landing Neil Armstrong and "Buzz" Aldrin on the Moon in the summer of 1969.

For Cernan, the Moon had come so tantalizingly close. But he would one day return to the Moon, and not only walk on its surface, but drive there, just as Wernher von Braun had predicted.



Apollo 17 Lunar Module *Challenger* is prepared for stowage inside the Spacecraft Lunar Module Adapter of its Saturn V after having completed its final checkout inside the Manned Spacecraft Operations Building at Kennedy Space Center. LRV-3 is visible behind and to the right of the crew ladder. (NASA)

APOLLO 17 CREW SELECTION

The cancellation of three Apollo missions and the reshuffling of the surviving missions, ending with Apollo 17, caused considerable consternation in the Astronaut Office. Eugene Cernan, Ron Evans and Joe Engle had been backup crew for Apollo 14 and, based on Deke Slayton's established crew rotation, these three would be the prime crew for Apollo 17. However, high level discussions had been taking place in Houston regarding the last crew. Johnson Space Center Director Robert Gilruth and Associate Administrator for Manned Space Flight, Dale Myers, agreed that Harrison "Jack" Schmitt should be part of that crew. Schmitt had come to NASA from the USGS in 1965 as part of the first group of scientist-astronauts, culled from 1,400 original applicants. It was a very select group of six candidates announced in June of that year. It included Joseph Kerwin, Edward Gibson, Curtis Michel, Duane Graveline, Owen Garriott and Schmitt, who was the only trained geologist.

Schmitt had helped to develop the geologic field training program for the Apollo

Boeing technicians prepare to remove LRV-3 from its shipping fixture using the Sling Hoist in order to secure it to the Handling and Installation Tool (HIT). The LRV remained on the HIT for the remainder of its inspections, equipment checkout, and mission simulations. (NASA)

astronauts. He had also been involved in overseeing the development of the ALSEP by Bendix Aerospace. Each Apollo astronaut was assigned to oversee the development of either particular hardware that the astronauts would use directly, or hardware that would be used in support of the mission. This proved to be a brilliant stroke because it gave the Astronaut Office an inside man who would know a specific piece of equipment or system intimately and who could convey the progress or development problems to the other astronauts who would be using it. This kept all the astronauts in the loop with regard to the equipment they would all be using during their missions.

The crew of Apollo 15 had returned from their immensely successful mission on 7 August 1971 and the Apollo 16 crew of Young, Duke and Mattingly were in the midst of their mission training. It was rumored that Slayton would soon make his announcement regarding the crew selection for Apollo 17, the last American mission to the Moon for what would likely be many years. Gilruth and Myers had made it clear to Slayton that they wanted Schmitt on the crew of Apollo 17. Slayton had immense respect for Gilruth and Myers and their views carried considerable weight. In the first week of August, Slayton telephoned Cernan and Evans with the news. Slayton congratulated Cernan, saying that Apollo 17 was his to command and that Ron Evans would be his Command Module Pilot. But Slayton needed to discuss the selection of Lunar Module Pilot. Cernan was in Slayton's office in Houston the next day and Slayton told him that Jack Schmitt was the choice for Lunar Module Pilot. Cernan was surprised, but accepted the decision. On 12 August 1971, Schmitt received the call from Slayton informing him that he had been selected to be Lunar Module Pilot for Apollo 17 and the following day, Slayton formally announced the three as the prime crew of Apollo 17. The backup crew would be John Young and Charlie Duke, the prime crew of Apollo 16, along with Stuart Roosa.

"The neatest thing about Schmitt going on Apollo 17 was that he was a professional geologist," said Bill Muehlberger, Principal Investigator of the Field Geology Team on Apollo 16 and 17, to this author during our interview. "I can't think of anyone else in the world at that time who was better qualified to go to the Moon and do geology."

APOLLO 17 LANDING SITE SELECTION

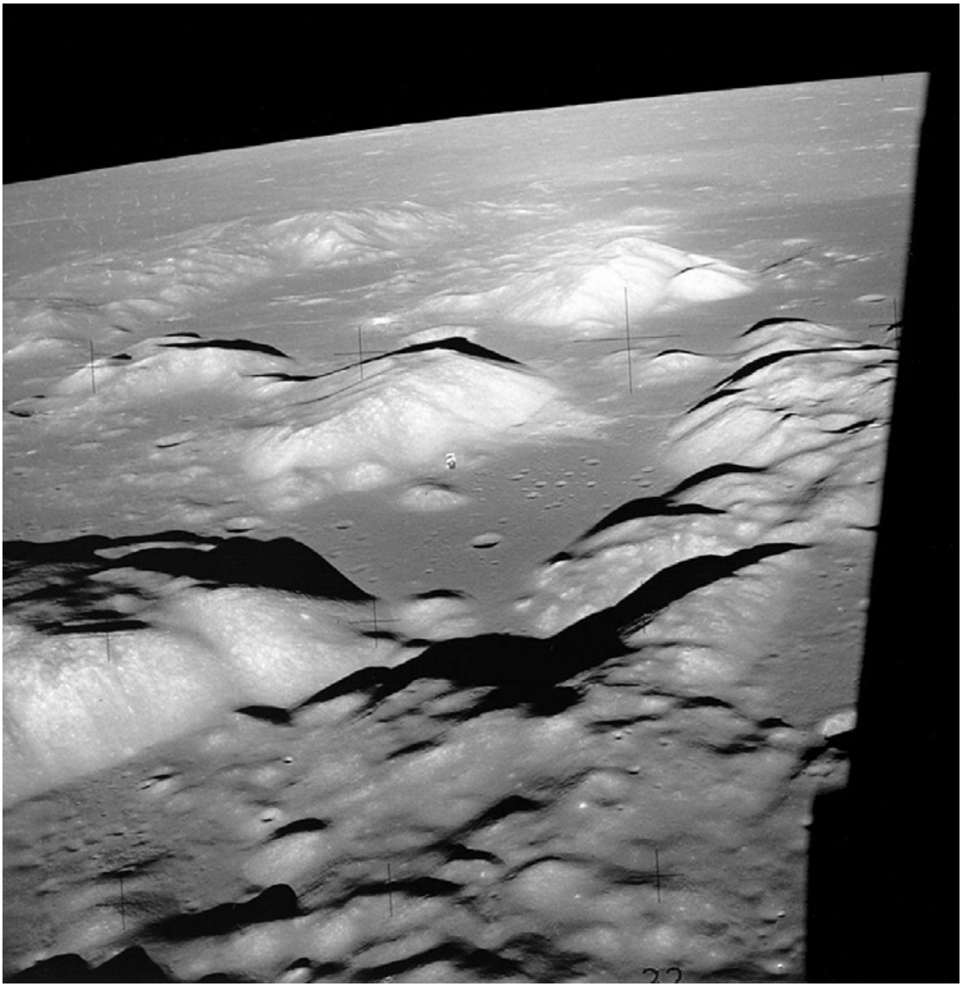
Deliberation on the landing site for Apollo 17 actually began during discussions regarding the landing site for Apollo 16 because the Apollo Site Selection Board (ASSB) considered the last two lunar landing missions complementary in their preference for lunar highlands. When the ASSB met on 3 June 1971 to select the Apollo 16 site, it also wanted to designate a prime site candidate for Apollo 17. The principal debate for the Apollo 16 landing site was between Descartes and Alphonsus on the eastern edge of Mare Nubium. When Descartes was selected as the site for Apollo 16, that moved Alphonsus to Apollo 17 as the prime candidate site. However, the ASSB wanted to wait for the orbital photographs of the highlands

from Mare Crisium to Mare Serenitatis from Apollo 15, as well as gamma ray and X-ray data along the spacecraft's orbital path. In October, the Board reviewed the Apollo 15 photographs taken from the Service Module mapping camera, together with the other data. Four of the six potential landing sites considered from this review were eliminated. The two remaining potential sites were added to the three other high-priority contenders. The five sites under consideration for Apollo 17 now included Alphonsus, Copernicus central peaks, Gassendi central peaks on the northern rim of Mare Humorum, a site southwest of Mare Crisium, and a highlands-volcanic site, designated Taurus-Littrow, on the southeastern edge of Mare Senenitatis.

In December 1971, a Site Evaluation Document was issued to thirty-two evaluators, including the principal investigators, co-investigators and other scientists involved with experiment packages, and mission planners. The responses evaluated by the Ad Hoc Site Evaluation Committee in January 1972 established a consensus of objectives that included (1) orbital science coverage, (2) sampling early volcanics, (3) sampling pre-Imbrium highlands as far from the Imbrium basin as possible, (4) traverse geophysics, and (5) the Apollo Lunar Surface Experiments Package with priority placed on the heat flow experiment (lost on Apollo 16). The responses also weighed in with site preferences. From this, the committee narrowed their short list to three potential sites in order of preference. First was Taurus-Littrow, second was Gassendi and a distant third choice was the crater Alphonsus.

Initially, NASA's Mission Planning and Analysis Division (MPAD) doubted that a landing could be achieved at Taurus-Littrow. The key issue was orbital mechanics and, specifically, what MPAD referred to as the three-sigma-error ellipse. The landing site was the farthest east of any lunar landing site. Once the Lunar Module came out from behind the Moon, there was a limited amount of time to enter the state vector into the LM's computer prior to powered descent. There were also issues with guidance, tracking, and modifying the landing techniques to make it feasible. Several months of work between MPAD and Bellcom, Inc. (which was contracted by NASA to advise on this and other issues related to lunar missions) transpired before all the precise factors necessary for landing at Taurus-Littrow fell into place.

On 11 February 1972, the Apollo Site Selection Board met to select the landing site for Apollo 17. Gassendi presented problems; if the Lunar Module touched down outside the landing ellipse, the crew would not be able to reach the prime objective of the central peaks, even with the LRV. For this and other reasons, Johnson Space Center considered Gassendi unacceptable. The ASSB then focused on Alphonsus and Taurus-Littrow. It was felt that superior orbital coverage and better potential for use of the LRV at Taurus-Littrow made the choice relatively easy, so the ASSB recommended Taurus-Littrow as the landing site for Apollo 17 to the NASA Associate Administrator for Manned Space Flight, Dale Myers.



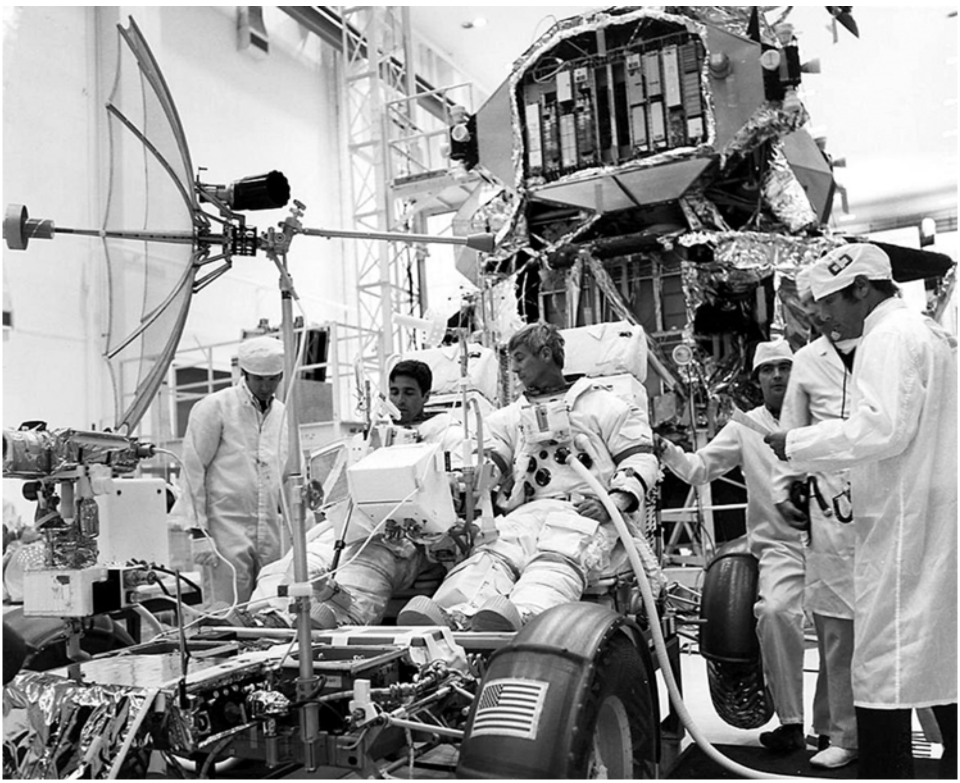
The Apollo 17 landing site of Taurus-Littrow was named after the Taurus Massifs (mountains) and Littrow Crater. The latter was named in honor of Joseph Johann von Littrow, who was director of the Vienna Observatory in the early 19th century (NASA)

MISSION AND EVA TRAVERSE PLANNING

With the selection of Taurus-Littrow as the landing site for Apollo 17, mission and EVA transverse planning commenced. The lunar mission was made up of scientific experiment deployment and geologic exploration, but there was also science and photography to be performed by the Command Module Pilot while in orbit around the Moon. Jack R. Sevier was Chairman of the Traverse Planning Subcommittee of the Science Working Panel, and was assisted by Dr. Robert. A. Parker, Apollo 17

Mission Scientist, who would also act as the EVA CapCom. Sevier had the Herculean task of integrating the lunar surface experiments with the pressing requirements of the geologic teams and the missions operations teams so that the timeline allocated to the astronauts on the Moon was orderly, achievable and did not tax their stamina. These planned traverses were also sent to MSFC, where the LRV traverse team of Otha "Skeet" Vaughan and E.C. Smith, as well as the electrical and the thermal teams, could run Power Profile Analysis and thermal models to predict power consumption and temperatures. Mission and EVA planning was also essential to establish training procedures. Some aspects of this training had already been established, such as LRV deployment and outfitting, but there were subtle changes with regard to new sampling tools and other equipment.

The Apollo Field Geology Investigation Team was responsible for planning the geologic exploration at Taurus-Littrow and for preparing the crew for the scientific tasks to be performed on the lunar surface. It would also provide geologic guidance



Capt. Eugene Cernan (right) and Harrison Schmitt photographed in August 1972 on LRV-3 during vehicle and Lunar Module tests inside the High Bay of the Manned Spacecraft Operations Building at KSC. The LRV sits on a stand to protect the flight unit from damage. (NASA)

during the mission EVAs through the Mission Control CapCom, and would interpret the results of the field observations. William Muehlberger was the Principal Investigator and he was joined by more than two dozen of the most experienced and respected geologists and scientists involved with lunar science and exploration. Practically all of them had been involved with previous Apollo missions. Lunar Module Pilot Harrison Schmitt, who would be on the lunar surface with Eugene Cernan, was also part of the geologic consortium that established the detailed geologic exploration plans.

Orbital photography from Apollo 15 and geologic maps of the Taurus-Littrow region in 1:250,000 scale, 1:50,000 scale and 1:25,000 scale, served as the basis for planning the EVA traverses in detail. As with Apollo 15 and 16, the availability of the Lunar Roving Vehicle allowed the planning teams a wider radius of operations from the Lunar Module. This time, it could encompass the North Massif, the South Massif, the Sculptured Hills, and numerous sizable craters, as well as the scarp within Taurus-Littrow. Littrow Crater was, in fact, far to the north and well outside the area to be explored. Up to now, most of the craters within the valley of Taurus-Littrow were unnamed, but for the purposes of mission and traverse planning, they would have to be identified. Harrison Schmitt was actively involved in this effort and his choices reflected his interests in literature, geology, exploration and the history of western man. Eugene Cernan contributed several names, as did Robert A. Parker and geologists James Head, Edward Wolfe, and Beth Williams.

"We couldn't have done without it," Muehlberger said of the LRV's contribution to Apollo 17 EVA planning during our interview. "That's the reason we landed at these more complex landing sites. We knew we had the rover, which would save us energy and consumables. You could stay out longer. They also had better space suits, so instead of five-hour capability, you had seven. Both of those things contributed mightily to our planning. Apollo 17 was different in the sense that we had incredibly good photography. The Apollo 15 Service Module mapping camera from sixty-five nautical miles above the lunar surface gave us two-meter resolution. That really gives you a different capability in planning. We could see these huge boulders that had rolled down the sides of the massifs, and some went all the way to the bottom. That is why, of course, we went to those specific boulders, because we could put them back up there where they belonged, so to speak, and maybe that way get a little better geologic context into how that eight-or nine-thousand-foot massif face was put together. That was our rationale for sampling those big boulders."

With this mission, the primary EVA traverses using the LRV were established by September 1972, but considerable planning also went into contingency traverses. There was a contingency traverse plan for one astronaut on the LRV, which eliminated the first EVA traverse but essentially kept the traverses planned for EVA-2 and EVA-3. In the event of the LRV not functioning upon deployment, contingency walking traverses were planned for each EVA that entailed shorter distances and fewer sampling stops. There was a traverse plan in the event that the Lunar Module landed as far as 2.7 km north of the targeted location, and another covering a landing the same distance south.

PRE-LAUNCH ACTIVITIES

Flight hardware for Saturn Apollo launch vehicle SA-512, ultimately destined for Apollo 17, began arriving at the Kennedy Space Center in October 1970, with the arrival of the S-II second stage. The S-IVB third stage arrived at KSC on 21 December 1970, while the S-IC first stage arrived on 11 May 1972 and the S-IU instrument unit the following month. The Command and Service Modules (CSM) arrived at KSC in March 1972 and were placed in the altitude chamber in the Manned Spacecraft Operations Building (MSOB) to begin both manned and unmanned systems tests. The Lunar Module arrived from Grumman in June and was placed in a separate altitude chamber to undergo its own series of tests, both manned and unmanned. Assembly of the Saturn V's S-IC first stage on Mobile Launcher 3 inside the VAB began on 15 May. Assembly of the stack continued with the S-II second stage, then the S-IVB third stage and finally the Instrument Unit, and was completed on 27 June.

The Lunar Roving Vehicle, LRV-3, arrived at KSC on 2 June 1972 and, after inspection in the MSOB, began its scheduled tests and mission simulations with Cernan and Schmitt that summer. Several changes had been implemented on this rover. An electrical cable had been installed to connect the new Surface Electrical Properties experiment to the LRV Signal Processing Unit (SPU) navigation computer to provide vehicle location data to the SEP. New fender extension stops were installed on all fenders, an index ring was added to the azimuth alignment dial on the Low-Gain Antenna, and there was a minor change to the aft pallet latch.

In July, the LM and CSM were removed from their test chambers. The landing gear was installed on the LM and a deployment test of the LRV from the LM was conducted on 10 August. LRV-3 was installed for flight on the descent stage of the LM on 13 August. The LM was encapsulated in the tapered Spacecraft Lunar Module Adapter (SLA) and the CSM assembled to the SLA the following week. On 24 August, the assembled spacecraft were moved to the VAB and mated to the launch vehicle stack. The topping off ceremony consisted of securing the Launch Escape System to the Command Module. Rollout of the space vehicle from the VAB to Pad 39A took place on 28 August and the first "plugs in" test and Flight Readiness Test were conducted in October. These were followed by the Countdown Demonstration Test, in two phases. The first involved fueling the Saturn V and taking the countdown to 8.9 seconds – just prior to ignition – fully fueled. Then the launch vehicle was drained of its fuel, and a second test conducted with the prime crew aboard and simulated fueling of the Saturn V.

This magnificent launch vehicle, the largest and most powerful rocket in the world, and one so inherently complex, was made up of millions of parts. It was one of the greatest engineering achievements of the twentieth century – a monument to the indomitable will of man to achieve the near-impossible goal of reaching the Moon. SA-512 was the last Saturn V that would launch astronauts on that epic journey. The ground support team continued to monitor and run systems checks on the Saturn and CSM through November and the countdown for launch began at 08:30 EST on 30 November 1972. The launch of Apollo 17 was scheduled a few days

Apollo 17 was the only manned lunar mission launched at night due to the timing of the trans-lunar injection burn and the location of the Taurus-Littrow landing site. The launch was visible hundreds of kilometers away. (NASA)

later, on 6 December. Three days before launch, the LRV's batteries were installed in the vehicle, the battery monitor cable and equipment hooked up and the batteries load tested, as had been done on Apollo 15 and 16. The batteries were once more monitored up to eighteen hours before launch.

THE NIGHT LAUNCH OF APOLLO 17

Days before the scheduled launch of Apollo 17, all the motel rooms in Cape Canaveral, Titusville and the surrounding small towns were booked. This last launch of Apollo brought in the news media from across the United States and from around the world. Many individuals traveled by car and motor home from as far away as California and Alaska to find any place they could park their vehicle to see the majestic Saturn V in the distance. All of them wanted to be part of this historic event. It was also historic for another reason, as it would be the only launch of the Saturn V to take place at night, with liftoff scheduled for 9:53 p.m. This decision was the result of orbital mechanics. The Trans-Lunar Injection for all previous Apollo lunar missions was initiated over the Pacific Ocean. However, Taurus-Littrow was not accessible using the TLI burn over the Pacific in December. It could only be achieved by launching at night and initiating the TLI over the Atlantic Ocean.

Jim Sisson, MSFC Acting Project Manager for the LRV in Huntsville, had been at the Cape to ensure that the LRV's batteries had been fully charged, that there had been good readings on both batteries before it had been closed out, and that there were no other issues with the LRV. He had had a long day on 5 December and got into bed just before midnight. At 3:00 a.m. the following morning, he was awoken from his sleep by a phone call from the Crew Quarters in the Manned Spacecraft Operations Building.

"Commander Cernan wants to talk with you," the individual calling said.

"OK," Sisson said, and then waited.

"He wants you out here," was the response. Sisson threw some cold water on his face, got dressed and left the motel for KSC. He went through three security checks before he was finally inside the Manned Spacecraft Operations Building. He was led to the room near the Crew Quarters where the astronauts were having their breakfast. Sisson sat down in front of Eugene Cernan with Jack Schmitt sitting next to him. Cernan leveled his gaze at Sisson.

"Are the batteries OK?" Cernan asked him.

"Yes, the batteries are OK," Sisson replied with total confidence.

"That's all I wanted to know," Cernan told him. Sisson wished them success on their mission and left. The LRV had performed reliably on Apollo 15 and 16 and Sisson felt it would do so again on Apollo 17.

Later that day, Cernan, Evans and Schmitt underwent their physicals, then went for the first pre-launch supper. After their meal they suited up and, just a little over three hours before launch, took the transfer van out to Pad 39A. Night had fallen and the powerful searchlights bathed the Saturn V in brilliant light. The crew took the Launch Umbilical Tower elevator to the top and walked across the swing arm to the Command Module *America*. They were once again assisted into their couches aboard the capsule by Guenther Wendt and his crew. The hatch was locked and the blast protective cover over the hatch installed and then the closeout crew left the pad. The countdown proceeded smoothly, the weather was perfect and everything was go for launch. At T-50 seconds, the Saturn V went on full internal power – and then something occurred that had never happened on an Apollo Saturn V launch before.

At T-30 seconds, the Terminal Countdown Sequencer (TCS) failed to command pressurization of the liquid oxygen tank of the Saturn's third stage and the automatic cutoff of the countdown was triggered. The launch was put into a hold to ascertain the problem. With amazing speed, engineers at the Marshall Space Flight Center determined that there was a faulty diode on one of the printed circuit boards inside the TCS. Using a breadboard, the engineers devised a jumper to circumvent the defective part, ran the necessary tests, and received the required approvals for this action. Launch director Clarence Chauvin informed the crew of what was being done to resolve the problem, and that when it was resolved, the count would be recycled. With that reassuring news, Harrison Schmitt dozed off to sleep for about an hour. Two hours passed from initial cutoff before the countdown clock was recycled to T-22 minutes and the count resumed. The count successfully passed the 30-second mark this time and the ignition sequence started at T-minus 8.9 seconds. The crew of Apollo 17 lifted off at 12:33 a.m. on 7 December.

The Saturn V lit up the night sky with a nearly blinding light that was visible hundreds of kilometers away. All staging was nominal and precisely twelve minutes after launch, the crew was in their 93 nautical mile-altitude parking orbit. Several hours later, the S-IVB was fired again to start the push to Trans-Lunar Injection. Evans performed the transposition and docking maneuver to extract the LM and the Saturn third stage was vented and sent on to its planned impact location on the Moon on 10 December. The TLI time to the Moon was adjusted with a single 1.6-second Service Propulsion System burn to permit the spacecraft to arrive on time for its originally-planned Lunar Orbit Insertion burn. The spacecraft initially achieved a nautical mile orbit equivalent to 314.5 by 97.3 kilometers, adjusted later to 109 by 28 kilometers. At 14:35:00 GMT, Cernan and Schmitt left the CM *America* and entered the LM *Challenger*. They prepared themselves and the LM for descent, the CSM and LM separated on the twelfth orbit and Evans performed a circularization burn. Shortly afterwards, the Lunar Module's computer program initiated powered descent to the lunar surface at Taurus-Littrow.

LANDING AT TAURUS-LITTROW

"Ignition, Houston," Cernan reported. "Attitude looks good. Engine Override is On. Master Arm is Off. We got a Descent Quantity Light On at ignition, just prior to ignition." The twelve-minute powered descent phase would take the Lunar Module from its ten nautical mile altitude to the valley floor of Taurus-Littrow. Schmitt read off velocity and altitude as *Challenger* slowed and dropped out of its lunar orbit.

"When we pitched over at 7,000 feet [2,133 meters]," Cernan told this author during an interview, "we were already below the mountain tops. I mean, we were down there – we were in it! Once we pitched over in the valley, I almost felt like I'd been there before. I recognized a lot of craters. It was just a case of driving the vehicle down to where I wanted to land it. We landed in a valley that was surrounded by mountains on three sides higher than the Grand Canyon is deep, to give you an idea of what the terrain looked like, and at the far end of the valley there was what I

Harrison Schmitt takes a rake sample during the Station 1 stop on EVA-1, 11 December 1972. Cernan was impressed with the utter blackness of deep space as seen from the surface of the Moon. (NASA)

would call an escarpment but it was almost like a dam. If you could have filled this valley with water, that dam might have held it."

Cernan had done such a good job in landing the LM, avoiding craters and boulders before setting *Challenger* on the lunar surface, that there was nearly two minutes-worth of fuel left in the spacecraft's descent stage fuel tanks. Mission Control was going through all the telemetry data from the Lunar Module after landing, checking all the systems to be sure that the crew could stay there for the scheduled three days. Finally, the crew got their "Go" to remain on the surface from CapCom Robert Parker in Houston. The two astronauts wasted no time describing what they saw out the LM's windows. For the first time, they were experiencing $^1/_6$ gravity, after they released themselves from the restraints. It proved a pleasant

sensation. They continued through their Surface Checklist, had something to eat and drink and then started their EVA-1 preparations and donning their suits and helmets. Only four hours would pass between the moment *Challenger* touched down and the two astronauts standing on the lunar surface. The Commander was first down the ladder.

EVA-1: AN EVENTFUL DAY

"I'm on the footpad," Cernan stated for Mission Control. "And Houston, as I step off to the surface at Taurus-Littrow, I'd like to dedicate the first step of Apollo 17 to all those who made it possible." The Lunar Module Pilot soon followed Cernan to the lunar surface. Cernan found getting adjusted to $\frac{1}{6}$ gravity was easy.

"You adapt very quickly," stated Cernan during the author's interview. "One-sixth gravity is the greatest environment you could live in, far better than zero gravity, certainly, and far better than Earth gravity because you can move so much more easily and quickly. You just have to plan ahead. You still have the same amount of momentum and inertia as far as getting around. One-sixth gravity is absolutely a phenomenal environment to live in and work in."

Cernan informed Houston that he would inspect the folded Lunar Rover stowed in the LM descent stage.

"Okay, Bob. So far, the Rover looks pretty good," Cernan told Parker.

"Roger; sounds good, Geno," Parker acknowledged. Cernan then removed the protective thermal blanket between the rover and the LM descent stage.

"Everything I can see looks pretty good," Cernan told Houston. "The walking hinges, you will be glad to know, are intact! They did not drop."

"Roger! That's a first," Parker replied. The walking hinges on Apollo 15 and 16 had to be reset prior to deployment.

"You ready for me to deploy?" Schmitt asked after he climbed the ladder and reached for the D-ring lanyard that would release the rover from its locked position and rotate it out several degrees.

"Okay. Let me just double-check," Cernan said. "Drape, contingency, unstow aft deployment cable, verify walking hinge, forward and aft chassis parallel. They are."

After Cernan verified that the outrigger cables were taut, Schmitt released the rover. Together, the two astronauts succeeded in deploying the LRV in just over fifteen minutes. The forward and aft chassis locking pins had to be manually set with a special tool designed for that purpose. Cernan climbed aboard the rover to verify it was drivable before it was fully configured with all its equipment and tools. He read the battery and motor temperatures off to Houston and then threw the switches on Control and Display Console before trying the rover out.

"Okay. I can't see the rear ones, but I know the front ones turn," Cernan announced. "And it does move. Hallelujah. Hallelujah, Houston! *Challenger's* baby is on the roll."

"Roger. Copy that. Sounds great," Parker answered.

"And judging from the way it's handling, I think the rear wheels are steering too,"

The right rear fender of the rover was damaged during EVA-1. An expedient fender repair was needed and worked out at Johnson Space Center. Surface map covers, duct tape and AOT clamps from the Lunar Module proved an effective solution. John Young (left), Charlie Duke, Deke Slayton, Rocco Petrone and Ron Blevins review the finished repair. (NASA/JSC)

Cernan guessed. Schmitt verified that the rear wheels were also turning. The Boeing, GM and MSFC engineers and managers smiled and nodded at the news. Apollo 17 had its rover, and it was shaping up to be a great mission. Schmitt took several photographs of Cernan driving the stripped-down rover. After parking the LRV near the LM, the two astronauts began to outfit it for their first EVA. Cernan loaded the communications equipment on the front of the rover, while Schmitt configured the back of the LRV, beginning with the Aft Pallet Assembly and Lunar Hand Tool Carrier, the Traverse Gravimeter Experiment, and sampling tools and bags. Cernan completed setting up the telecommunications equipment and powered on the TV camera and the LCRU.

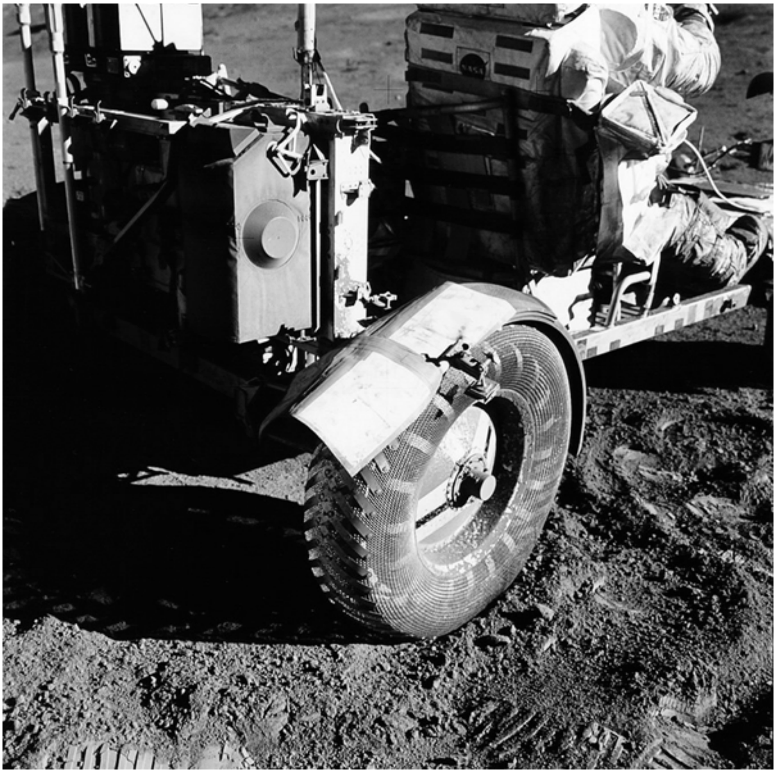
"Hey, we have a picture, 17. We have a picture," Parker acknowledged, as Ed Fendell began operating the TV camera from his console in Houston. Cernan went to the rear of the rover to initialize the gravimeter and get the first reading. Nothing could be loaded on the LRV while the TGE was operating in order to get an accurate reading, so the astronauts deployed the American flag and took turns photographing each other next to it, with *Challenger* and the LRV in the background. This flag was particularly significant, as Schmitt explained for all those listening.

"Houston, I don't know how many of you are aware of this, but this flag has flown in the MOCR (Mission Operations Control Room at the Johnson Space Center in Houston) since Apollo 11. And we very proudly deploy it on the Moon, to stay for as long as it can, in honor of all those people who have worked so hard to put us here and to put every other crew here and to make the country, United States, and mankind, something different than it was."

The next important task was deploying the ALSEP, which Schmitt performed. Of all the Apollo astronauts, Schmitt was the most knowledgeable regarding the ALSEP, having been involved with its design almost from the beginning. This ALSEP was different, having some experiments carried over from previous missions, but with several new experiments. Some additional experiments would be deployed during traverses. The heat flow experiment, the lunar geology investigation, the cosmic ray detector and the soil mechanics experiment returned for Apollo 17. New experiments included the Lunar Surface Gravimeter, Lunar Ejecta and Meteorites, Lunar Seismic Profiling, Lunar Atmospheric Composition, Lunar Traverse Gravimeter, Surface Electrical Properties and Lunar Neutron Probe. The last of the ALSEPs was the most sophisticated piece of equipment ever deployed on the Moon. Prior to deployment, the ALSEP was configured like a barbell, with experiments on each end of the bar, so the astronaut could walk to the deployment site about 100 meters from the LM. Schmitt was perhaps the most relaxed of all the Moonwalkers, and would occasionally break out in song while doing his tasks. Deployment of the ALSEP would be methodical and deliberately slow, not only to ensure proper placement from the Central Station as planned, but to avoid destroying any cables by snagging them with one of their boots, as John Young had done on Apollo 16.

A fender crisis averted

As Schmitt made for the deployment site, however, it would be the LRV that suffered some inadvertent damage.



Instructions for the fender repair were transmitted to the Apollo 17 crew. Pages from the USGS Lunar Surface Map Package were taped together inside the Lunar Module and then clamped to the damaged fender. It worked surprisingly well. (NASA)

"Oh, you won't believe it," Cernan moaned.

"You did it again," Schmitt answered, thinking Cernan had hit the wrong button on the gravimeter experiment.

"No! There goes the fender," the Commander replied. Cernan had stowed the lunar hammer in his shin pocket and, as had also happened with Young on Apollo 16, the hammer snagged on the right rear fender extension and pulled it off its extension rails. Jim Sisson couldn't believe it had happened again. Lunar dust was the enemy of thermal control, and Ron Creel and the others working in the LRV support room knew they had a potential problem on their hands in trying to maintain proper operating temperatures for the electronic equipment. This would also make Cernan and Schmitt's suits filthy and the lunar dust would foul the closures and seals. Keeping their visors and camera lenses free of dust would also be a problem. Despite being a fine powder, lunar dust was extremely abrasive and would scratch the visors of their helmets.

"I hate to say it, but ... I'm going to have to try to get that fender back on," Cernan told Parker.

"Okay. Was it the rear fender, Geno?" Parker asked.

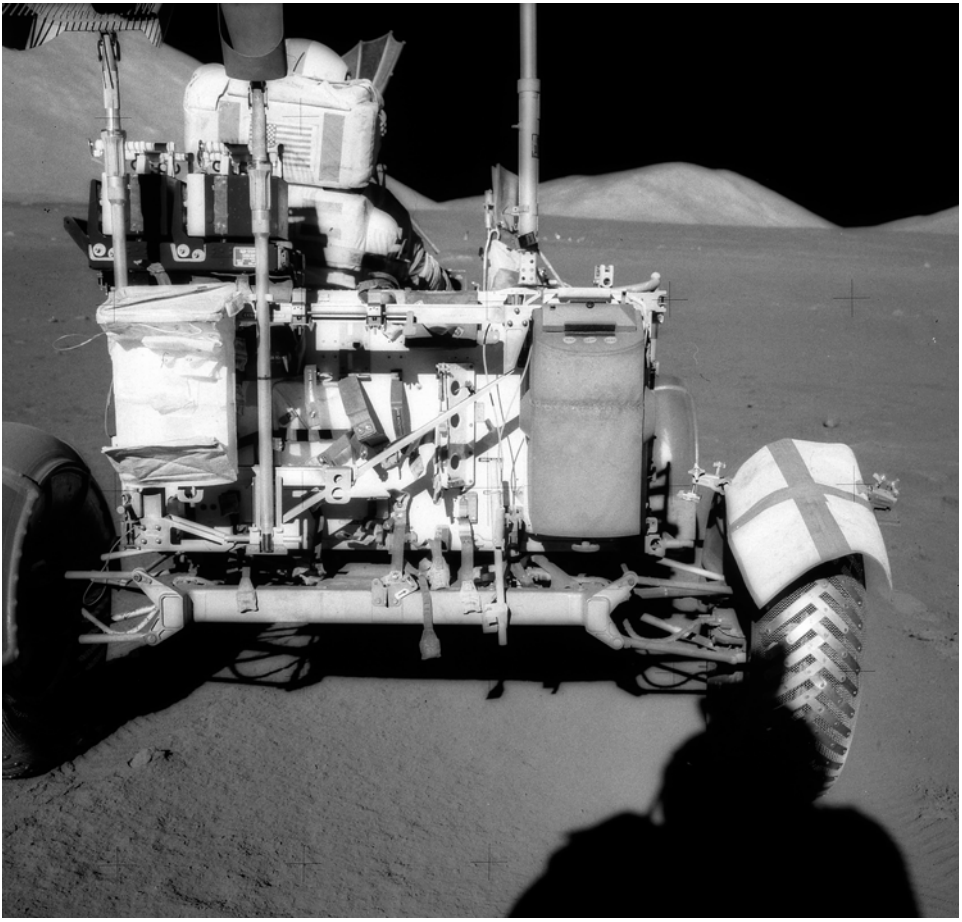
"Yeah. Caught it with my hammer, and it just popped right off." Cernan asked Schmitt if the roll of gray duct tape was under the Commander's seat of the rover. Schmitt said it was, and Cernan said he might have to use it. Schmitt, meanwhile, was exerting considerable effort in carrying the ALSEP out to the deployment site. While it weighed only ⅙ of the several hundred kilograms it weighed on Earth, it still had mass and Schmitt's breathing was noticeable. He had to go to maximum cooling on his PLSS.

"Well, if it wasn't for that fender, I'd be ready to go," Cernan remarked. "Makes me sort of mad! Well, I've done this in training. I can't say I'm very adept at putting fenders back on, but I sure don't want to start without it." Cernan retrieved the tape from under his seat, picked up the fender extension and placed it back on the fender, only to find that one of the extension rails had broken off. Ed Fendell kept the TV camera on Cernan as he proceeded with his fender repair. With amazing dexterity, Cernan peeled off strips of gray tape and attempted to tape the extension to the main fender. It was not a perfect fix, but he managed to tape the extension temporarily in place.

"I think it'll stay, for an indefinite period of time right now," Cernan told Houston. "Not bad for EV gloves."

Cernan quickly read from his Cuff Check List and verified that the rover was configured before driving out to the vicinity of Schmitt's ALSEP site. He turned the TV camera around, shut it off, climbed on the rover and then reported the battery temperatures, which read 100 and 120 degrees F, to Houston. Parker directed him to orient the LRV up-Sun after he had parked eighteen meters north of the ALSEP site and to then open the battery covers. With the rover facing the Sun, the open battery covers would shade the battery radiators and permit them to radiate heat to open space. Cernan realigned the High-Gain Antenna and Houston could now watch the rest of the ALSEP deployment. While Schmitt was leveling and deploying the ALSEP, Cernan removed the drill core stems from the back of the LRV. He assembled the first stem with a solid pointed tip to the drill and began to drill the hole for the first heat flow probe. The heat flow experiment was the creation of Dr. Marcus Langseth, its Principal Investigator. It proved strenuous work, with Cernan's heart rate exceeding 130 beats per minute, and he had to rest numerous times before he reached the required depth of 2.5 m. He then sank another hole for the second heat flow probe. The bore stems were left in place and Cernan pushed the probes to the bottom of each hole using a special rod designed for the task. He then placed a radiation shield over each hole. Meanwhile, Schmitt was busy deploying the Geophones around the ALSEP site. Near the third Geophone was a small boulder, dubbed Geophone Rock, which Schmitt surmised had been blown out of Camelot Crater. It was Schmitt's first chance to do geology since they had landed. Despite being twenty minutes behind the EVA timeline, he worked quickly to identify the rock's structure and took photographs. He was able to identify pyroxene and plagioclase and what appeared to be brown glass.

Houston had a superb picture of the lunar activities of Cernan and Schmitt from the rover's TV camera. Those images were the result of new technology first



Jack Schmitt took this photo prior to EVA-2 at the SEP site. The South Massif is to Cernan's left and Family Mountain is in the distance. The gray device on the Lunar Hand Tool Carrier near the replacement fender is the Traverse Gravimeter. (NASA)

employed during Apollo 16. In 1971, John Lowry launched a new company called Image Transform in North Hollywood, California. Lowry had worked for years in the film and TV industry and had developed the means of dramatically improving the image quality of video tape-to-film transfers. He received six image processing patents at the time for video noise reduction and other related developments. He was given some video footage from Apollo 15 to clean up, and the results impressed even Lowry himself, improving the video signal-to-noise ratio by 3 to 6 db. He felt he could make a contribution towards improving the video images for future Apollo missions and in February 1972, two months before the launch of Apollo 16, Lowry met with Col. James McDivitt at the Manned Spacecraft Center in Houston. Lowry brought with him three short clips from Apollo 15 to show McDivitt, of both before and after the image transfer process. McDivitt was impressed and Lowry's company

was contracted to process the video images beamed to Earth from Apollo 16. During that mission, the video signal was beamed to Earth from the High-Gain Antenna on the rover to the big dish in Goldstone, Arizona and was then sent to Houston and on to North Hollywood, where the Image Transform process was applied. Then it was sent back to Houston. The Australian ground stations at Parkes, Honeysuckle and Sydney performed that duty when acquiring the signals beamed from the Moon. Image Transform was also contracted to process the video for Apollo 17.

Cernan's next task was to sink the deep core sample tube. He had to lean on the drill for a third time, but after sinking the tube to its desired depth, could not extract it with the drill. He had to use the jack and treadle to pull the compacted core tube stems out. The core tube was extracted inch by inch, but Cernan's heart rate rocketed up to 150 beats per minute and his labored breathing was clearly audible. The flight surgeon urged CapCom Parker to tell Cernan to take a break and the astronaut willingly complied, switching his PLSS to maximum cooling. Schmitt had to go over and assist Cernan in extracting the core tube and together they finally succeed in extracting the recalcitrant tube. They completed their remaining tasks and sample collection, but by this point they were nearly forty minutes behind their timeline for the EVA. Their stop at Station 1 would have to be shortened, with Cernan also having consumed more than the planned amount of oxygen in his PLSS. They got ready for their traverse to Station 1.

"You haven't been on the Rover yet," Cernan told Schmitt. "It's real easy; but it's also very easy to kick dust all over those battery covers [Cernan meant battery radiators], so don't even get on it until I put those battery covers down."

"Yeah. Hey, I guess we ought to press on as if we're going to Station 1," Schmitt answered.

On to Station 1

Bill Muehlberger and the Apollo Field Geology Investigation Team in the Backroom had been looking forward to the Station 1 stop, southeast of Emory Crater as originally planned. The valley at Taurus-Littrow was heavily cratered, and Emory was one of the larger craters, measuring 650 m in diameter. This had to be eliminated as a station stop, however, and the two astronauts would stop near Steno Crater instead, which was just as big. Cernan shut down the TV camera, aligned the navigation system, and the two astronauts set off on their first traverse on the rover. This would be the shortest traverse of their three EVAs. As with the two previous Apollo missions, when the astronauts were driving the rover, communications were transmitted from the astronauts' PLSS through the Low-Gain Antenna mounted on the LRV to the LM and then from the LM to Earth. The reverse path was followed during communications from Earth to the Moon. After traveling some distance from the ALSEP site and about 150 m from the LM, the crew deployed the transmitter for the Surface Electrical Properties (SEP) experiment. This had been conceived by Gene Simmons of MIT and an experiment team, in conjunction with Marshall Space Flight Center, to measure the dielectric properties of the lunar surface and subsurface. Cernan and Schmitt would return to the SEP site later to lay out the dipole antenna grid which would transmit the data being collected. The receiver and

recorder for this data was kept on the LRV and would be returned to Earth at the end of the lunar mission.

Since they were running behind in their EVA timeline, they made a stop about 150 m from Steno Crater to place the first seismic charge. They would take their samples from a small crater with a considerable amount of blocks and small boulders at that location. Cernan read off the rover's coordinates, temperature and remaining amp/hours on the batteries, and the motor temperatures. When he got off the rover he found the taped fender still in place.

"Okay, the fenders are still on, thank goodness," Cernan exclaimed after he got off the rover.

"Beautiful. We'll give you the Taper of the Year award," Parker replied.

"Bob, you're going to want a core at this site?" Schmitt asked Parker.

"Roger. Number 1 priority will be some block samples, including any dirt that was on the blocks, if there is such. And then the second priority is a rake soil sample; the third priority is a double core. Then, also in there, the pans, of course, and other

During the traverse to Station 6 for EVA-3, Cernan and Schmitt encountered this group of boulders. The largest was named Turning Point Rock and measured 6 meters high. The LRV's TV camera was always pointed backward during traverses. (NASA)

documented samples. But the double core is there, although it is third priority,'' was the detailed response from Houston. This would be a thirty-minute stop as they took rock, soil and rake samples, chipped small rocks from the small boulder, and took photographs, but Houston then advised them that the core samples were deleted. Cernan had aligned the High-Gain Antenna and turned on the TV camera. While they were there, they described their observations for the benefit of the scientists in the Backroom. They placed their samples in the bags and then the sample collection boxes. All too soon, they had to stow their tools, get aboard the rover and head back to the LM. Along the way, Schmitt gave detailed descriptions of their lunar surroundings.

''Okay, Houston. There's the classic raindrop pattern over this fine debris. I'd say that the surface definitely is sorted: the fine regolithic material forming one fraction and then the blocks another. Those blocks greater than 2 cm in diameter, in general, make up (that is, cover) less than ten per cent of the surface, but there are some big ones, fairly uniformly distributed. There are blocks a meter in diameter.'' Cernan had to concentrate on driving the rover and avoiding blocks and craters, but Schmitt had the opportunity to take pictures with his Hasselblad from the rover.

''It responded as you might expect in ⅙ gravity,'' Cernan said of the LRV. ''You hit a bump, you hit a crater, [and] you're going to go up on three wheels half the time. We had a limited horizontal velocity of about twelve to fourteen kilometers per hour. It handled very well. I didn't have any problems with it.''

The lunar dust problem returns

The only problem Cernan and Schmitt did have with the rover was the loss of the right rear fender extension. The temporary repair Cernan had made using the tape failed on their return to the LM.

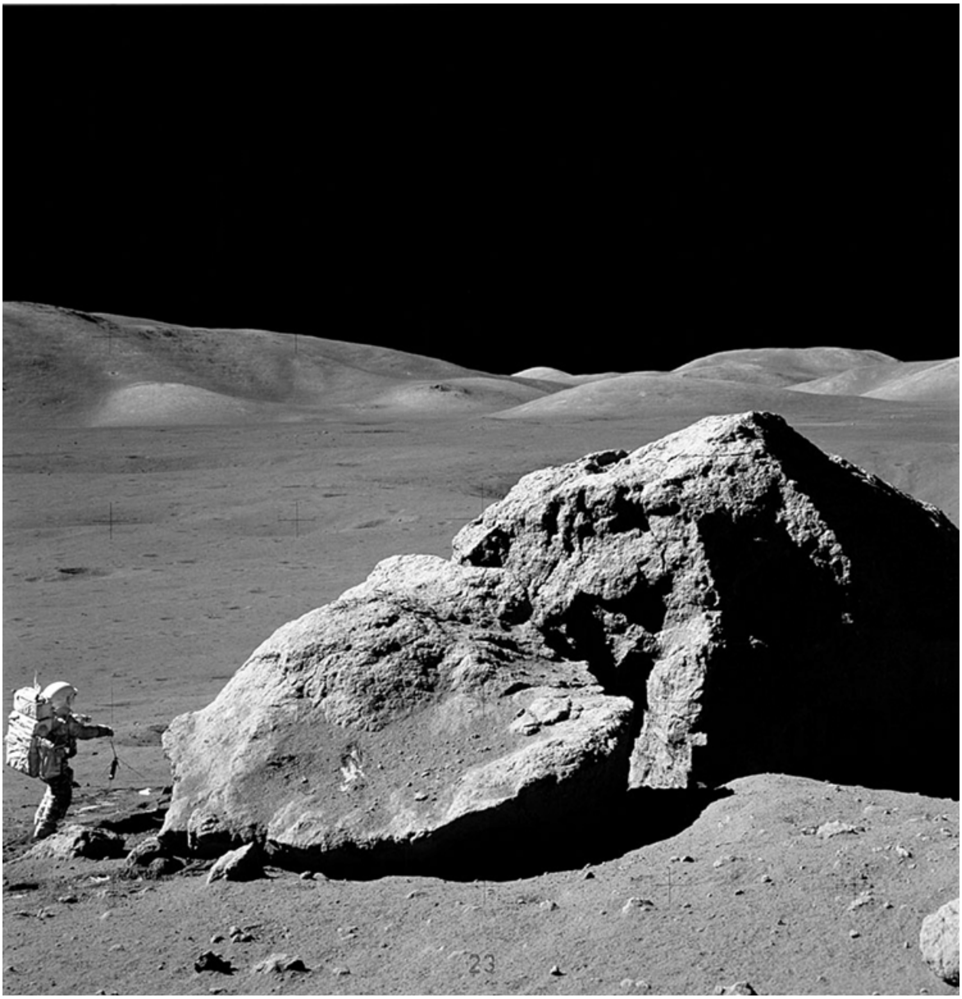
''I think you have lost a fender. I keep getting rained on here,'' Schmitt remarked.

''Oh, no!'' the Commander exclaimed.

''Look at our rooster tail,'' Schmitt observed. ''Look what's ahead of us here.''

''Yeah, that's probably it. It probably didn't stay. I can see it in the shadow.'' Due to the direction they were traveling and the angle of the Sun, Cernan could see the shadow of the lunar soil being thrown up and forward.

''Look at that fender. Look at the dust it's produced. Look at the LCRU,'' Cernan added as they headed for the Surface Electrical Properties (SEP) site, clearly concerned. Cernan wasn't the only one concerned. The engineers listening in the LRV management interface control room of the Huntsville Operations Support Center (HOSC) knew the missing fender extension would wreak havoc on the LRV's electrical systems, because extra dust was being deposited on the dust covers and could then get into the space radiators and increase the temperatures of the electronics. Cernan and Schmitt had not even completed their first EVA and already the lost fender extension was creating problems, not just for the LRV but for the astronauts' suits as well. A solution to this problem would have to be found, and the telephone lines between Houston and Huntsville came to life to work on the problem. In the meantime, Cernan reinitialized the LRV's navigation system in order to get a true north-south and east-west orientation and used the LRV to lay out



The Station 6 stop was this large split boulder near the base of the North Massif. Cernan climbed up the steep slope above the boulder to get this photo. Schmitt sampled the lunar soil thrown onto the surface of the boulder after its impact. He is carrying the gnomon. (NASA)

tracks so that the SEP antenna wires would be accurately deployed. At the intersection of the tracks, Schmitt placed the transmitter and together they unreeled the antennas, measuring 35 meters from the transmitter.

"Oh, boy; the thing that makes me sick is losing that fender. I can stand a lot of things, but I sure don't like that," Cernan complained as he helped lay out the antennas. "Man, I hate this dust. I got to make a new fender tonight."

"Hey, Gene, I presume that the fender that came off is the fender that came off before, right?" Parker asked.

"Yeah, same one. My tape didn't hold; it was too dusty," Cernan said. They finished configuring the SEP and Schmitt collected some larger samples and placed them in the Sample Return Container. The missing fender extension continued to haunt Cernan. Minutes later, he voiced his concern again.

"Boy, that one fender just is an order of magnitude more of a dust problem," Cernan remarked as he dusted off the LCRU and battery covers. Schmitt offered to help with the dusting task.

"Well, I need a fender, that's what I need. Figure out something we can make a fender with," he said to Schmitt as well as to Mission Control in Houston.

"How about one of the others that's not as critical?" Schmitt queried.

"Yeah, but I wouldn't ever take one of those off! You know, I had one to put on and it didn't stay, which is what I figured."

"I thought you said it was broken, though?"

"Well, it was," Cernan answered. "But these aren't supposed to come off, either, unless you break them. I broke that one. My hammer got caught underneath it. It wasn't the fender's fault."

Minutes later, a curious event occurred involving the LRV's High-Gain Antenna. Schmitt and Cernan were stowing samples in bags and then containers, when Cernan noticed flying debris.

"What are those things going over? What is that, Jack? Hey, something just hit here!" Cernan looked around to try to determine what had occurred. "What blew? Hey, what is that?"

"Oh, your antenna . . .It's that Styrofoam off the High-Gain Antenna package," Schmitt observed.

"On the LM?" Cernan asked.

"No, the one you deployed. The Rover's High-Gain Antenna," Schmitt explained, just as another piece of insulating foam exploded from the antenna.

"My God, it blew up!" Cernan stated in amazement.

"Yeah," Schmitt said in response.

"Look at that stuff, it just keeps flying over the top of our heads! I thought we were the closest witnesses to a lunar meteor impact. I wonder if that's the same glass I picked up?"

"John says it blew up on his mission too, guys," Parker said, when John Young relayed the information to Parker that the same phenomenon had happened during Apollo 16. Cernan prepared to configure the LRV's circuit breakers before leaving to return to the LM.

"One thing we'd like before you guys leave the rover is a fairly good description of what happened to the rear fender when it came off. Is the damage primarily to the piece that you've lost, or are the rails on the pieces remaining fairly bad?" Parker asked.

"Well, a piece of the rail on the aft inboard side here . . ." Cernan said, pausing as he looked at the damaged fender. "The rail isn't missing; it's just a piece of the flange, the rail that fits against the fender [that's missing]. But that doesn't hold any part of the fender on. I don't remember what I saw on the [missing] fender. The rails look pretty good, Bob. And I had one of them completely on, and I just couldn't get

the other one on. If I had known what that dust was [going to be like], I would have tried an awful lot harder."

"Do you have any feeling that you could get away with putting a front fender on?" Parker asked, the question having been passed up to him from the LRV teams in Houston and Huntsville.

"Well, I have done it before, but it's not easy."

"Okay, as far as you can tell, so that we can look at it overnight, the rear fender – the part that's remaining – looks in fairly good shape, right?" Parker asked.

"Let me take a good look at it," Cernan answered. "Yeah, the part you need, I think, to hold that fender on."

"Okay, we'll take a look at it here while you're sleeping," Parker offered.

Cernan opened the LCRU blanket to 100 per cent and opened the battery covers. He had been diligent in keeping the LRV's critical components dusted periodically, but it was not just the rover but each astronaut's suit that had to be dusted off as much as possible. The lunar dust was tenacious, clinging to the fabric of their suits, metal surfaces and even their visors. They prepared to take their samples aboard the LM and completed closing out their first EVA at Taurus-Littrow.

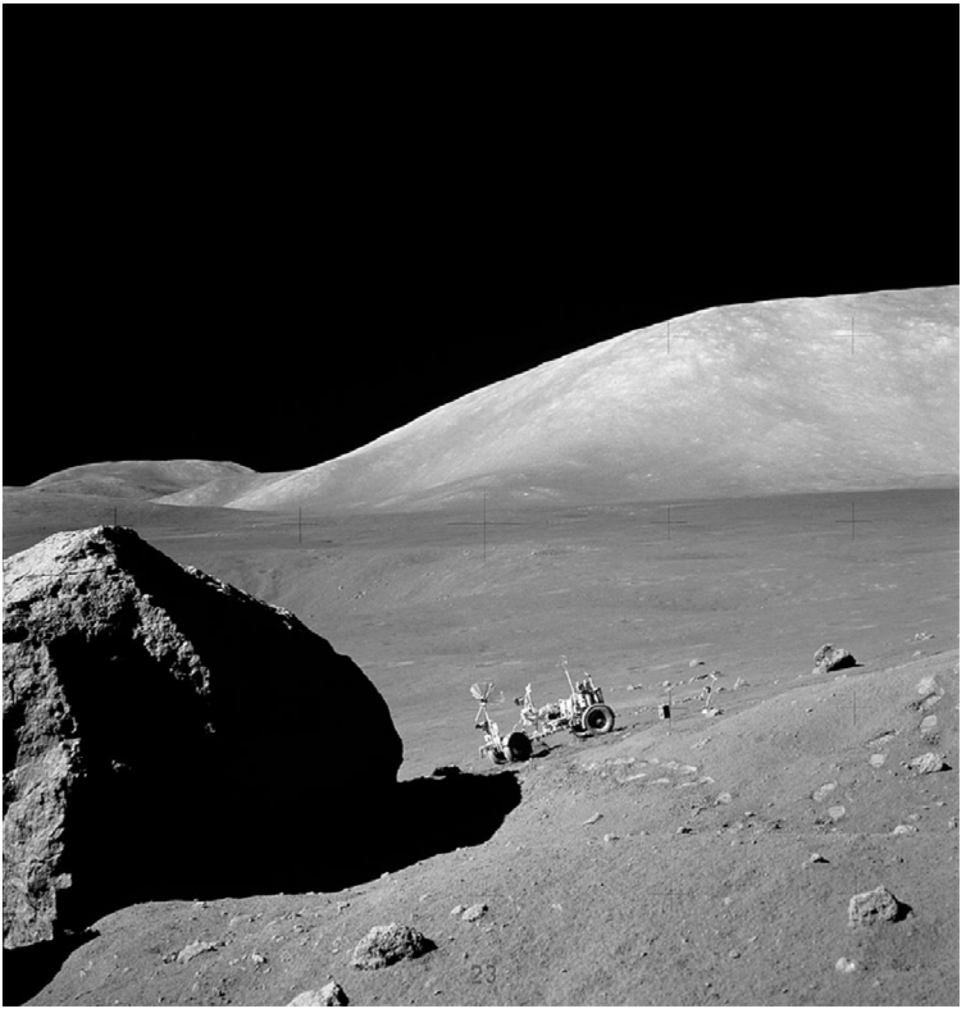
Back inside *Challenger*

Schmitt climbed in first and Cernan followed him into the cramped LM cabin, then closed and locked the hatch. The cabin re-pressurized and they could then depressurize their suits and remove their helmets and gloves. They had been inside *Challenger* about two hours when CapCom Joe Allen spoke with them about the planned repair to the LRV's fender.

"Troops, while you're in a listening mood up there, we're going to be coming at you with a number of items here. Not too many, but the first will be some surface block data," Allen informed them. "Then we're going to read up to you a LEVA (Lunar Extravehicular Visor Assembly) cleaning procedure which is fairly simple; a real short geology debrief; [and] a one-line change in the Lunar Surface Checklist. And then, we've been doing some thinking down here about how to fix the fender, and it's going to involve – we think, although we'll work on it while you guys are getting some rest – it's going to involve using utility clamps from inside your LM there, instead of tape, to fasten some sort of stiff material onto the rover in place of the missing fender. We'll go with either one of your cue cards, or possibly with part of the insulation that was the flame blanket protecting the rover during the landing. Or perhaps part of the packing material that was between the Rover wheels and is probably lying on the ground underneath the LM there."

"Joe, you couldn't be reading our minds more," Cernan responded. "We were talking about that, and there is a piece of it right outside my window. I saw it after we got in here. Either that or back of a part of a data book or something. I hate like the devil to tear one of those other fenders off. And the reason tape won't stick is that everything's got a fine coating of dust. The only way I could finally get it to stick was to put tape on it (and then) rip the tape off . . . which took some of the dust off and then (another piece of) tape would tend to hold it. But it just won't hack it up here."

"Roger, Gene," Allen agreed. "That's exactly what we're thinking and what we're



Another shot from the photographic pan Cernan took at Station 6. The angle of the LRV reveals the severity of the slope. The South Massif dominates the view in the distance. (NASA)

going to do is run through the fix in a pressure suit a few hours from now. If it looks like we can do it, and it won't cost you many more than say ten minutes, we're going to have you go through with it. If it takes longer than that, we're going to go back to the drawing board and see what else we can do here."

"Well, you know John and Charlie can tell you just how bad it is," recalled Cernan. "I wouldn't have believed it and I guess I didn't believe it, or I would have worked a little harder to make sure that fender was going to stay on. But, man, just that short trip back from where we lost it, we were just covered. I couldn't even read parts of the panel on the rover, plus all the battery covers and everything."

Cernan was relieved that Houston was right on the problem. He knew the gravity of the situation. If he and Schmitt had to constantly dust off the LRV's critical equipment, it would take them away from performing the exploration tasks that needed to be done. The broken fender had to be repaired, and it had to be a repair that would last for the next two EVAs. It also had to be a repair that could be implemented with their pressurized suits on. After Apollo 13, Cernan was fully confident there wasn't a problem that could not be solved by the resourceful crews on the ground in Houston and Huntsville.

The Apollo 17 Flight Crew Support Team was tackling the problem. Terry Neal was the Apollo 17 Lunar Module Crew Systems Engineer on the team, and he immediately went to work to see what could be used from the LM to fabricate a fix. Neal went to the area at Johnson Space Center where the mockup of the Lunar Module was kept, climbed inside the LM and looked around to see what might be used. He hit on the idea of using the stiff pages from the lunar surface maps, taping four of them together to create a curved fender surface big enough to do the job. Inside the LM, there were Alignment Optical Telescope (AOT) lamp clamps that could be removed and used to clamp the maps to the LRV's right rear fender. It looked like the idea might work, so he passed it on to the EVA procedures team, which was also part of the Apollo 17 Flight Crew Support Team. As Cernan and Schmitt slept, the procedures for fabricating the expedient fender and clamping it to the actual rover fender were being worked out with John Young and Charlie Duke.

EVA-2: SOLVING THE FENDER PROBLEM AND CRATER EXPLORATION

Cernan and Schmitt received some rousing wakeup music in the form of Richard Wagner's *Ride of the Valkyries*. Gordon Fullerton was the Wakeup CapCom, and after twenty minutes of essential preliminaries, he advised the crew regarding the repair to the LRV's fender.

"*Challenger*, Houston. We've been working, while you've been sleeping, on a fix for the missing fender. John Young has been over working it out in the suit with the mockup Rover, and we have about five to ten minutes-worth of words on how you want to go about that. Whenever you have that much time to listen – it'll be mostly listening on your part – let us know."

"Gordy, we're going to start to eat here. Why don't you talk to us about that fender?" Cernan said several minutes later. John Young was summoned to the Mission Control room and sat down next to Fullerton.

"Hey, we spent some time on this fender problem," Young said, "and worked out a pretty simple-minded procedure, which involves essentially taking four of those cronopaque pages out of your lunar surface maps – ones which are not going to be used for discussing the site – taping them together with gray tape so that you end up with a piece of paper about 15 inches by 10.5 inches. Then, using the AOT lamp clamps, pre-position them full opened, take them out (in the ETB), take that piece of paper out (of the ETB), lay it on top of the fender guide rails, and clamp the edges of it with the AOT lamp clamps. It's simple and straightforward, and the beauty of it is

The LRV's TV camera was trained on Cernan as he took this photo of the LRV at Station 6. Transmissions were beamed directly from the LRV's distinctive gold mesh high-gain antenna directly to Earth with unprecedented resolution. The LCRU's thermal blankets were occasionally opened during station stops. (NASA)

you're only spending about two minutes in the clamping operation, and it could save you up to about twelve [minutes of] dusting. What do you think?"

Cernan agreed with the concept and then clarified the details of how the map pages were taped together and clamped to the LRV's fender. The crew then continued with their preparations for the second EVA, and fabricated the *ersatz* fender repair as instructed in detail by John Young. Cernan stored the two AOT lamp clamps in his shin pocket as the two men suited up. They completed their checklist for the LM cabin, depressurized and descended to the lunar surface for their second EVA. Schmitt was particularly excited at the prospect of having a full

day of exploration ahead of them without having to deploy more experiments. They went through the Cuff Check List of loading camera magazines, sample collection bags and boxes and other tasks. Then, Schmitt helped Cernan with the fender repair. With John Young in the communications loop, Schmitt held the taped maps to the fender while Cernan clamped them securely. Ed Fendell had the TV camera trained on the two astronauts as they performed the fender repair so that John Young in Mission Control could watch their progress.

"Does that look good to John, from what he did?" Cernan asked.

"It looks exactly what he did, he says," Parker answered.

Towards the South Massif

Their destination for EVA-2 was the South Massif and their goal was to sample the light mantle that was so distinctive of the massifs in the valley. Cernan referred to the navigation page of his Cuff Check List, resorting to range and bearing instead of heading. They passed Camelot Crater on their right, one of the largest craters in the valley, and the one clearly seen by the astronauts during their descent to the lunar surface. They stopped the rover briefly for Schmitt to place another Seismic Profiling Experiment explosive package before continuing on what would be the longest traverse of their mission. As they traveled, they were able to identify craters with apparent ease.

"We can definitely see the light mantle as it comes out over the valley here, and we're looking at Hole-in-the-Wall, although it's still too subtle," Cernan reported. "We're looking right at Lara, as a matter of fact."

"Yeah. There's Lara, very clear; and Hole-in-the-Wall, you can see it," Schmitt agreed.

"There's Horatio way over there where those blocks are. See it?" Cernan asked his Lunar Module Pilot.

"Yeah, that's Horatio. We're right on course, sir. There's a little depression we didn't talk about, though, that's between Horatio and Camelot. But it's a depression and not a blocky crater at all. As a matter of fact, the total block population has changed. Once we get away from the rim of Camelot, the block frequency is quite a bit smaller. It's down, maybe to less than one per cent of the surface."

"Much easier driving with the rover," Cernan noted, with very few blocks to deal with. "Boy, am I glad we got that fender on. Very obvious that the rover navigation [was easier] because of the [scarcity of] blocks and because of the smaller craters, and very subtle type craters in this area."

They drove toward the South Massif and Nansen Crater, parallel to the Lee-Lincoln Scarp they would soon climb in the rover. The scarp was a plateau that ran between the North and South Massif. Schmitt had an opportunity to use the LRV Sampler, a new sampling tool, for the first time on this traverse. This tool permitted Schmitt to take soil and small rock samples from the lunar surface without leaving his seat on the LRV. The sampler held a stack of cups, which were sealed with a lid. Cernan made several brief stops so that Schmitt could collect samples from intriguing areas on their way to Nansen (named for a Norwegian polar explorer). Cernan was driving the LRV at an average 10 kph, thanks to a favorable Sun angle and the scarcity of blocks, but he still had to watch for small craters to avoid. Like Dave Scott

Harrison Schmitt rounds one of the large boulders at Station 6 with the LRV in the foreground. The LRV helped the astronauts reach challenging locations such as this, which would have been unreachable on foot. (NASA)

and John Young before him, Cernan realized that he could not take his eyes off the terrain ahead of them for an instant or they would quickly find themselves in a crater. Cernan reached the base of the scarp and they began their climb.

"I don't even think the rover knows it's going uphill," Cernan told Houston. "I've got about 3.7 or 3.8 amps," he reported. "See what's on top here." Cernan was impressed with the rover's hill climbing ability. For the benefit of the science Backroom, Schmitt continued his observations.

"Okay. Whatever makes up the light mantle – at least, the instant rock that it forms – is much lighter than anything we see [elsewhere]. Those fragments probably

are thirty per cent lighter than any fragments we see out on the dark mantle. And that's around the fresh craters. But it is not blocky.''

As Cernan made for the top of the scarp, he had to drive the rover in a zigzag pattern, both to avoid craters but also to ease traversing the steeper portions of the scarp. They were now driving over the light mantle and Schmitt made his observations. Cernan then pointed the rover directly uphill and continued doing eight to nine kilometers per hour. The rover soon slowed, however, and Cernan had to go back to driving cross-slope. From their position, they could see boulder tracks running down the Massif.

''Let me tell you, this is quite a rover ride,'' Cernan told Houston as they approached the northern side of Nansen Crater.

''It sure sounds like it,'' Parker agreed.

''But it's quite a machine, I tell you! I think it would do a lot more than we let it,'' Cernan added. Schmitt had been taking photographs during the entire traverse. When these photographs were examined back on Earth, they revealed how steep the scarp was that they had been climbing in the LRV. They had been driving for over an hour at this point, were beyond visually sighting the Lunar Module and were approaching the limit of their walk-back constraints. Cernan then turned the rover toward the northeast to ease alignment of the High-Gain Antenna once he stopped for Station 2. When he stopped the rover, he gave Houston the battery and motor readings and was asked to check the fender repair. It was still securely clamped. Cernan aligned the High-Gain Antenna and dusted the TV camera lens and soon Houston had a picture. Fendell panned the camera across an impressive site, with the face of the South Massif rising majestically behind the astronauts. They were surrounded by blocks and boulders and it was clear that this would be a particularly rich sample site. Cernan and Schmitt took soil, rake and chip samples from the nearby boulders, with Cernan describing the area for the scientists and geologists in the Backroom.

''When you look down into the bottom of Nansen, it looks like some of the debris that has rolled off the South Massif covers up the original material there that covers the north wall of Nansen. There is a distinct difference. You've got that very wrinkled texture in the north slopes of Nansen, and you've got the South Massif debris in the south slopes of Nansen. And the debris, of course, overlays the north slope. And all the rock fragments, all the boulders that have come down, are all on the south side of the slope of Nansen.''

Unexpected discoveries

The men were given an extra ten minutes at Station 2, remaining there for over an hour sampling and photographing the area. One of the last photos Cernan took before mounting the rover was the now-famous image of the right rear fender repair, with Schmitt in his seat. Cernan powered down the TV camera and climbed aboard the LRV and they set out for Station 3. Houston requested the astronauts to stop after driving for several minutes to get a gravimeter reading, which required them both to get off the rover so that it was perfectly still to obtain a proper reading. They also took samples and more photos. After eleven minutes at Station 2A, they prepared to leave and continue on to Station 3 while driving over the Lee-Lincoln

Scarp. How the scarp was formed was another of the lunar mysteries the geologic team hoped to get answers to, but the visual descriptions Schmitt and Cernan gave Houston did not unravel the mystery. Even after the mission was over, Muehlberger and the other scientists pored over the mission photos to try to better understand the scarp's formation.

The stop at Station 3 was near the rim of Lara Crater, which had been deformed by the scarp. Here, Cernan drove core tubes into the surface with a hammer, not the drill. He extracted the core tubes and capped them, while Schmitt took samples and bagged them, and dug a trench. He also took a station photographic pan. The astronauts had been out on their second EVA for over four hours and did not feel taxed. They once again returned to the rover and made for Station 4, stopping briefly along the way for Schmitt to take an LRV sample from his seat. The undulating terrain resulted in the LCRU digging into the lunar surface, Cernan reported, but there was no effect on communications. The unit continued to perform perfectly.

The stop at Shorty Crater, the destination for Station 4, would become the most famous of the entire mission. Schmitt made a startling discovery, after making certain that the color of the soil was not the result of reflections from the rover's LCRU.

"There is orange soil!" Schmitt announced.

"Well, don't move it until I see it," Cernan said.

"It's all over! Orange!" exclaimed Schmitt in disbelief.

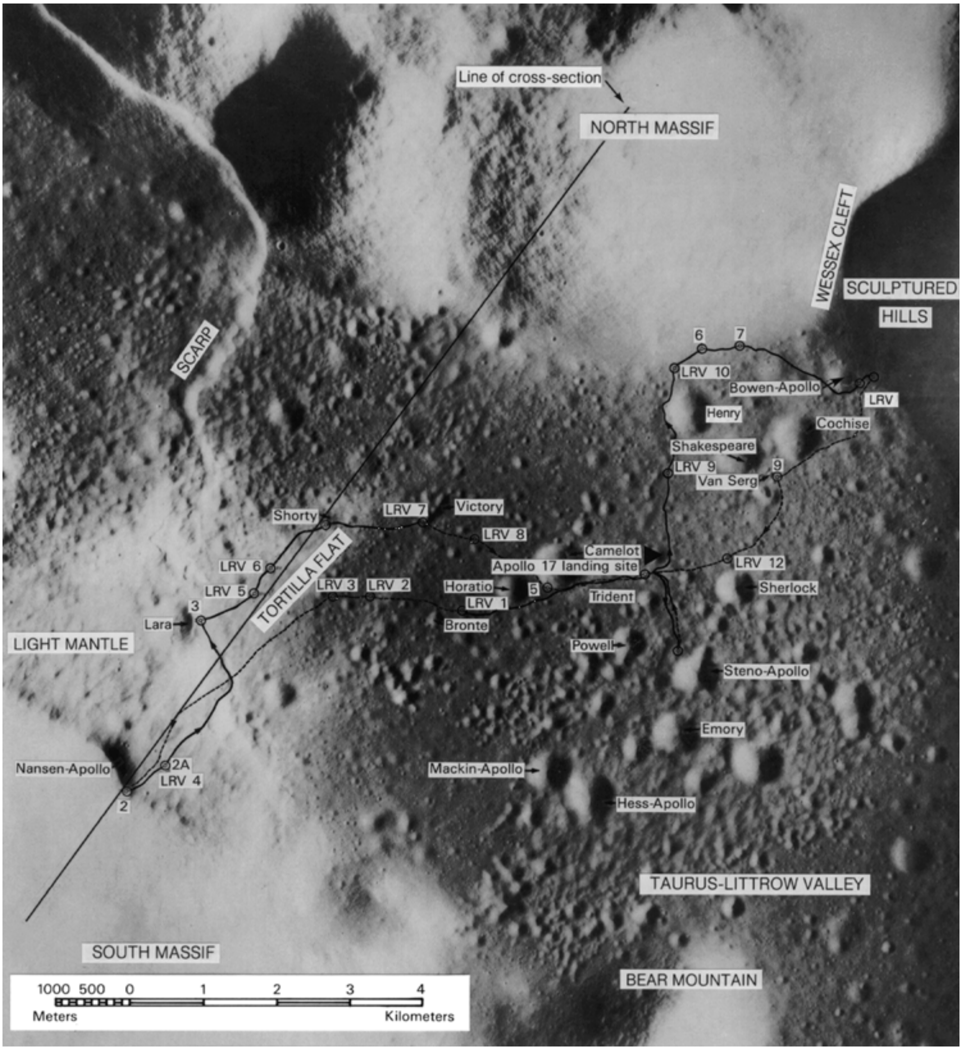
"Don't move it until I see it," Cernan repeated.

"I stirred it up with my feet," Schmitt remarked, ignoring Cernan's request.

"Hey, it is! I can see it from here!" Cernan agreed. Schmitt immediately set to work digging a trench and photographing the area. Ed Fendell made sure he had the TV camera trained on the astronauts. They were nearly five hours into their EVA and Houston was aware of the walk back constraints imposed by the PLSS. Parker asked Cernan to sink a double core in the area, which he drove in with his hammer. Toward the end of their sampling efforts, Cernan noted a warning flag alerting them that Battery 2 temperature was at 132 degrees F as they finally got on the LRV, but this had been predicted and expected. They had spent just over thirty minutes at Station 4 before heading on to Station 5 and Camelot Crater. During their traverse they spotted Victory Crater and did a rover pan, with Schmitt taking the photographs as Cernan drove the rover in a tight circle. Cernan then stopped the rover to allow Schmitt to gather a sample from his seat with the LRV sampler.

"Time was the most critical thing on the lunar surface," Cernan said in his interview with this author. "We never had enough of it but [at least] with the rover, we could not only shorten the distance between places we needed or wanted to go or desired to go, but we could also do some geology on the way – both picture taking and rock sampling while we were on the rover."

The traverse to Station 5 took them thirty minutes. Parker told Cernan and Schmitt they had twenty-five minutes at Camelot Crater for sampling and photography. Camelot measured roughly 600 m in diameter and the emphasis in sampling was on the sub-floor basalt material. Schmitt walked over to some nearby boulders and wasted no time in giving the science Backroom his observations. The



This photo traverse map of the actual route and location of the station stops at Taurus-Littrow differed somewhat from the initial traverse map, which typically happened on the Apollo J-missions. This flexibility was part of the mission plan. (Cambridge University Press)

two astronauts broke samples from some of the many small boulders littered around the area and described them both before and after breaking them off with the hammer. They also took soil samples with the scoop. The amount of boulders and rocks at Station 5 required the astronauts to be very careful in their movements to avoid tripping and falling down on them, as many of them had sharp edges.

"Okay, and a reminder, 17 . . .," Parker told the crew, "that the primary priority is

the blocks and then a rake of the white sub-floor soil there. And you've only got fifteen minutes before we want you driving back to the LM. Over."

Cernan and Schmitt worked methodically to collect the desired soil samples, though the rake sample was dropped due to time constraints. Cernan took a photographic pan of the area and when Schmitt reached the rover, he took a photographic pan as well. Cernan picked up the gnomon and hopped back to the LRV and they both stowed their samples and tools on the rover. They were reluctant to leave Camelot due to the variety of boulders and rocks. Cernan read off another gravimeter reading for Houston. He had parked the rover on a slope with the Commander's seat toward the uphill side.

"The thing Jack didn't like is when I'd be on the side of a hill, and he was on the downhill side," Cernan said in his interview with the author. "It always felt like you were going to fall over, or roll over. Being the Commander and the driver, I kept Jack on the downhill side most of the time. It was pretty uncomfortable for him because in ⅙ gravity, it didn't feel like the rover was held to the lunar surface very strongly." Cernan and Schmitt buckled themselves in and drove along the south rim of Camelot toward *Challenger*. It had been a productive EVA and they were in good spirits.

"Hey, here's some rover tracks!" Cernan reported to Houston in mock surprise.

"Hey, somebody's been here before," Schmitt agreed. Parker in Houston was all business, however, and reminded Schmitt of the need to deploy seismic charge No. 8. Cernan reported he had driven the rover 19.3 km. This was roughly 1.7 km further than the estimated straight-line station-to-station distance due to having to drive around craters during the traverse. Cernan stopped the rover a short distance from the ALSEP site, and they got off.

Closeout of EVA-2

Cernan read the requisite LRV numbers off to Houston, with battery temperatures at 114 and 138 degrees F. The temperatures of three of the traction drive motors were below nominal (read as "off-scale low" to Houston) but the forward right motor was at 210 degrees, though this was still well below the 400-degree upper limit. The rover had continued to perform perfectly and the fender repair was holding well. Schmitt took Cernan's camera to take photos of a nearby glass-lined crater and collected a sample from the crater which he carefully placed inside a sample bag. Cernan carefully dusted off the battery covers and reported they were the cleanest he had ever seen. Ed Fendell panned and tilted the TV camera toward the battery covers to prove it.

"Hey, congratulate Jose (John Young) on that fender will you?" Cernan told Houston. "Because I think he just saved us an awful lot of problems. He and whoever else worked on it."

The astronauts spent the rest of the EVA going through the closeout procedures on their Cuff Check Lists. Cernan turned off and stowed the TV camera and performed other tasks to prepare it for their last EVA the following day. Before re-entering the Lunar Module, they spent over six minutes dusting each other off as best they could, with the legs of their suits having the most dust to remove. Even so,

they brought more lunar dust into the LM than desired. By the time the hatch was closed and the cabin pressurized, Schmitt and Cernan had set an EVA record of seven hours and thirty-seven minutes for their second EVA. They took off their helmets and gloves and the pungent odor like spent gunpowder once again filled their cabin. Parker thanked the crew for a superb job that day, and handed over CapCom duties to Joe Allen.

Nearly two hours into their post-EVA checklist and discussion of the day's exploration, the subject of the Lunar Rover came up. Allen had been discussing the metabolic rate of both Cernan and Schmitt with the astronauts. As it turned out, the LRV had made a dramatic, positive impact on the astronauts' metabolic rate. During the ALSEP deployment and at the various station stops, the metabolic rate for both astronauts was over 1,000. While riding on the rover, it dropped to well below 500. The rover not only provided the means of getting the astronauts across considerable distances on the Moon for exploration and a means of carrying the necessary tools and collected samples, it also provided a needed period of rest that energized the astronauts. Interestingly, Cernan's metabolic rate while driving the rover was higher than Schmitt's, most likely because of the concentration he needed while driving.

"Actually, Joe," Cernan explained for the benefit of Houston, "for good long spans of the run up to Station 2, except when we had to pick our way up to Hole-in-the-Wall, I was running full bore at anywhere from, I guess, ten to twelve to fifteen clicks. I didn't hit fifteen going up (to Station 2) very much. Coming down I did, but it's really a 'standby for a turn and watch where you're going' type of run, because the small craters, of course, are the ones that can really jolt you. But the trouble is, you can never see what's just over the next ridge. The next ridge may be twenty meters away and you just can't see it until you're there, and you don't know whether it's a dish crater or whether it's a pit crater."

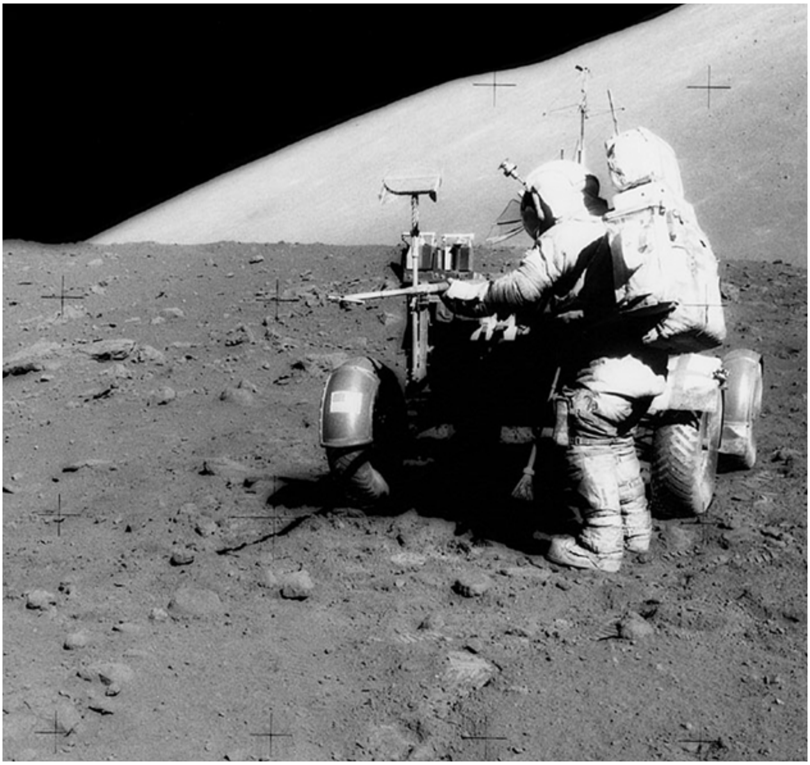
"That description fits the geology up in there," Schmitt added, "because we weren't seeing blocky rimmed craters; otherwise you would have been able to tell more easily about the old versus new craters, which would be the ones you could either go through or not go through, respectively."

"That's a super machine to drive though, Joe, I'll tell you," Cernan said of the LRV. "If you had enough time you could really learn to take it all the way. But you don't really do that, just the second time around."

"Geno, was it spraying dirt at you today?" Allen asked for many in Houston and Huntsville concerned about the fender repair and its effectiveness. "Could you notice that you still missed the real fender and that the patched fender wasn't quite doing what maybe it could?"

"No, sir, I don't think we missed it at all," Cernan answered positively. After some more discussion of preparations for their evening's sleep period and installing their sleep hammocks, the discussion shifted to future lunar exploration missions.

"Gene and Jack, we're still marveling at the beautiful television pictures that we're getting from your TV camera there," Allen said enthusiastically. "It's fun, in fact, to watch the tracks that you're leaving behind in the lunar soil, both footprints and



At Station 9, Cernan drove a core tube into the lunar surface and after extracting it, separated the core tube sections using tools at the back of the LRV designed for this task. (NASA)

rover tracks. And some of us down here now are reflecting on what sort of mark or track will – someday – disturb the tracks that you leave behind there tomorrow.''

''That's an interesting thought, Joe, but I think we all know that somewhere, someday, someone will be here to disturb those tracks,'' Cernan with assurance.

''No doubt about it, Geno,'' Allen agreed.

''Don't be too pessimistic, Joe. I think it's going to happen,'' Schmitt added.

''Oh, there's no doubt about that,'' Allen stated. ''But it's fun to think about what sort of device will ultimately disturb your tracks.''

''Joe, I'll tell you it's also a pretty philosophical thought to think that you're riding around out here on what is really undisturbed everything, you know,'' Cernan offered. ''If there was someone here, way back when sometime, they didn't leave much sign of their whereabouts, but that's an interesting thought, too, as you drive around and all of a sudden cross your own rover tracks and figure out those are the only ones that maybe have ever been here.''

The astronauts climbed into their hammocks and could not help but reflect on all the day's activities and discoveries they had made. Cernan, in particular, often felt that being on the Moon was a surreal experience – a reality almost too hard to

believe. It was not something he felt compelled to share with anyone. He kept it to himself, at least until he returned to Earth and shared his experiences on the Moon with his family.

EVA-3: THE LAST DAY ON THE MOON

Gordon Fullerton, the Wakeup CapCom, roused Cernan and Schmitt from their sleep at 160 hours and 25 minutes GET to start the third and last day of Apollo 17's exploration of Taurus-Littrow. It was Wednesday, 13 December 1972. Throughout the entire mission, the Earth was lower to the Moon's horizon than for any other Apollo mission, and Cernan described the Earth's continents that were visible from the Lunar Module's window. Robert Parker soon came online as the CapCom for EVA preparations and the day's surface activities. Parker went over the station stops and updated Cernan and Schmitt on the subtle changes to the day's planned activities. Unlike Apollo 16's third EVA, the astronauts would have a full day's schedule, with over seven hours on the surface. Cernan was first on the lunar surface again and Schmitt followed several minutes later. They went about the preliminary surface duties as per their Cuff Check List. The rover's LCRU TV camera was powered up and Ed Fendell got the TV camera moving, and soon images of the astronauts' activities were visible in Mission Control. Cernan wanted to know the condition of the LRV's batteries and when he checked, got some disturbing news.

"Well, Bob, Battery 1 is 95 degrees and Battery 2 is reading zero," reported Cernan. "So we've got a gauge failure. In fact, it's not reading zero, it's off-scale low." This gave the mission support team for the LRV a start. Technicians from Eagle Picher, manufacturer of the LRV's batteries, met with members of LRV Mission Control in the Huntsville Operations Support Center and initiated tests on two backup batteries. The same condition was reported on these batteries. It was determined later that the probable cause was a shorted thermistor as a result of electrolyte leakage through the sensor bond. Nothing more was said about Battery No.2 as Cernan and Schmitt prepared to set out for Station 6 at the base of the North Massif. Cernan used the temperature gauge for Battery No. 1 as a probable indicator of the other battery, but the off-scale low indication remained for the rest of the EVA.

Towards the North Massif

Once on the rover, the lunar explorers drove four kilometers toward the North Massif and observed tracks marking the paths of boulders that had rolled down the face of the Massif. Roughly half way to their Station 6 stop, Schmitt took a soil sample using the LRV Sampler after Cernan had stopped the rover. They then came upon a sizable boulder in their path, and Cernan drove the rover completely around it as Schmitt took photographs. This boulder was identified as Turning Point Rock, estimated at more than six meters in height. As they moved on to the North Massif, Cernan spotted a large split boulder on the slope of the massif. This would be their Station 6 stop. This boulder had split into smaller boulders after rolling down the

Harrison Schmitt photographed Eugene Cernan next to the LRV at the end of the third EVA, with the South Massif prominently in the background. Note the reflection on the gold mesh of the high-gain antenna from the radiator surface of the TV camera. The thermal blankets of the LCRU are pulled back to help dissipate heat. (NASA)

North Massif, breaking apart when it finally came to rest. Cernan parked the rover on a heading of 107 degrees as Houston had requested, but he was on a considerable slope, which he and Schmitt conveyed to Houston. The dust covers were opened at this first science station stop. The High-Gain Antenna was aligned and the TV camera turned on. Cernan recalled for this author just how challenging the slope at Station 6 was.

"Where that boulder was, I took the pan, those pictures of the boulder and the valley," he said during the interview. "That hill was on the North Massif and that doesn't look very steep, but let me tell you that was a *very* steep hill. I had to climb

up there and I left the rover down by the rock, and you can see how the rover is leaning. That was a very steep hill.''

While Schmitt examined the split boulder, Cernan walked around the rover to dust portions of it off. The steepness of the slope and the angle at which the rover was parked made it difficult to get around the vehicle. Cernan continued to comment on the severity of the slope they were on. The split boulder itself was on an even steeper portion of the slope, as Cernan had mentioned. Together, Cernan and Schmitt took samples from around the boulder fragments and shadowed soil samples from beneath the boulder overhang. Then Cernan retrieved his hammer and chipped some pieces from the boulder itself. The astronauts made sure to take before and after photos of the sampling area before putting the samples in their respective bags. Schmitt gave his detailed observations of the boulder for Houston. Later in their Station 6 stop, Cernan reported visible dents in the wire mesh on two of the rover's wheels, and Bob Parker wanted more specific information from Cernan.

``A little golf-ball size or smaller indentation in the mesh. How does that sound to you? Doesn't hurt anything,'' Cernan replied matter-of-factly.

``That sounds like a dented tire; that's how it sounds,'' Parker answered.

A core tube sample was also taken at the site. Cernan felt compelled to name the distinctive boulder Tracy's Rock, after his daughter. A portion of the boulder had a thick layer of lunar soil, which Schmitt had sampled, but Cernan wished later that he had written Tracy's name in the soil, where it would have remained for eternity. Cernan and Schmitt spent more than an hour at Station 6 before stowing their priceless samples and equipment and returning to the rover. They closed the dust covers, buckled up and moved on to Station. 7

The Station 7 stop was 475 m away from Station 6 near the base of the North Massif. It would be a short stop of ten to fifteen minutes. Cernan and Schmitt scouted for other boulders as they drove towards their next stop. Cernan stopped near a boulder more than two meters high and they got off to begin their sampling. They broke fragments off with their hammer and took further soil samples. Houston also wanted them to pick up a FSR, an acronym for a Football-Sized Rock. This EVA proved that the two astronauts were quite comfortable in handling their tools, taking photographs, communicating their observations to Houston, and moving about on the lunar surface. They stowed their samples and tools on the rover, climbed aboard, buckled up, and made for Station 8 near the Sculptured Hills, staying close to their EVA timeline.

Unlike the Cuff Check Lists used on Apollo 15 and 16, small traverse maps were included in the Cuff Check Lists for Apollo 17 at Eugene Cernan's suggestion, and they proved an immense aid to Cernan and Schmitt as they drove from station to station. Cernan later likened it to a geologic flight plan. On the way to Station 8, they spotted some boulders similar to those they had sampled at Station 6.

``It looks like they're probably the same thing that we sampled, Schmitt observed. ``They have the inclusions in them, white inclusions. They look like a mixture of the gray of the re-crystallized breccia, and the tan-gray of the anorthositic gabbro.''

The Sculptured Hills

"Let me tell you, this rover is a machine. I don't know if it saw that hill we're climbing, but I did," Cernan commented to Houston as they drove toward the Sculptured Hills. The terrain was undulating and far from flat. Cernan stopped the rover briefly for Schmitt to take a sample from a roughly 40 m dark-rimmed crater with scattered small blocks inside the rim. These turned out to be "instant rock," the phrase they used to describe lunar soil compacted by meteor impact. Geologically speaking, these were identified as clods that were ejected immediately after impact. Schmitt used the LRV Sampler to collect the samples.

"Your wheels are just chewing those things up," Schmitt said, commenting on the friable structure of the clods, being far weaker than the breccias that had once been molten and then cooled. Cernan found a suitable place to park the rover for the Station 8 stop, but once again the slope was severe enough to warrant him parking the LRV facing down hill so they could both get off the vehicle safely. Cernan had to perform his now-routine dusting duties to the LCRU, the Television Control Unit and the TV camera itself. He aligned the High-Gain Antenna and turned the TV camera on and Ed Fendell soon had the camera panning the entire site. Schmitt immediately went to work sampling and describing his discoveries.

"Our fender's beginning to fade," Cernan discovered, "and, uh-oh, the clip came off [the replacement fender but not the Rover] on the inside; that's what's wrong.

Video images from the LRV were picked up by tracking stations in Australia or Goldstone, California in the U.S. This is the video processing lab at the Honeysuckle Creek Tracking Facility in Canberra, Australia. (Colin Mackellar)

We'll have to fix that before we start. The outside one's holding, but the inside one's not.'' Cernan would deal with this before leaving Station 8.

``And we'd also remind you that we'd like a rake soil sample here, too,'' Parker reminded them. ``That may be the only way we can try to pick up some stuff other than sub-floor, if that has indeed come down from the top of the Sculptured Hills.''

After photo-documenting the rock, Schmitt pushed it down slope, but in ⅙ gravity, it moved slowly and soon stopped. Schmitt sampled the soil that had been under the rock, which went into bag No. 545. Cernan then pounded the rock with his hammer and broke off some sizable pieces for samples.

``This is about a 50-50 mixture of what looks like maskelynite or at least blue-gray plagioclase, and a very light yellow-tan mineral, probably orthopyroxene. It's fairly coarsely crystalline,'' Schmitt stated for the benefit of the scientists in the Backroom in Houston. Ed Fendell had been panning the TV camera over the entire site and this gave Bill Muehlberger and the other scientists enough information to request a rake sample near the rover, which Schmitt proceeded to collect. Schmitt and Cernan also took more photographs of the area. One of the last tasks at Station 8 was to secure the loose portions of the temporary fender under the clip. Dust had been thrown up on the right rear of the rover due to the loose fender fix.

``Boy, everything is stiff. Everything is just full of dust,'' Cernan exclaimed. ``There's got to be a point where the dust just overtakes you, and everything mechanical quits moving.''

Cernan succeeded in securing the temporary fender with the map clip and pronounced it fixed. Although not a perfect fix, this solution proved effective in keeping the dust problem to a bearable minimum. Lunar dust would indeed prove to be man's greatest challenge while on the Moon. Before future explorers return to the Moon, the effects of lunar dust on mechanisms, seals, air filtration systems and the astronauts themselves will provide an entirely separate field of study in pursuit of effective solutions. Cernan and Schmitt spent several more minutes making sure they had all their samples on the rover and their tools stowed. Cernan then powered down the TV camera and they climbed aboard the rover, buckled their seatbelts, and moved on to Station 9.

Van Serg Crater

Their next destination on the rover was the small crater identified as Van Serg. Measuring 90 m in diameter, it was far smaller than Henry, Shakespeare and Cochise craters near the North Massif. Those craters measured hundreds of meters in diameter. Van Serg appeared to be sharply defined from orbital photographs and Cernan and Schmitt were to sample its dark mantle and sub-floor material. They drove around the southeast, subdued rim of Cochise Crater and soon spotted Van Serg. They had been traveling at 10 kph or more, and the rover's wheels were taking a pounding over the blocky terrain. Cernan could not take his eyes away from front and center for even a couple of seconds, concerned as he was about hitting a football-sized rock that would jar them and the rover. He was constantly moving the hand controller left and right to avoid the larger rocks and the nearly indistinguishable small craters in front of them. At one point, the rover scraped over

Command Module Pilot Ron Evans photographed Cernan and Schmitt on their return home to Earth from their successful exploration of Taurus-Littrow. They were the last men to explore the Moon in twentieth century. (NASA)

one of the larger rocks passing underneath. They reported seeing dust coming over them and they suspected that the fender repair might have failed, but when Cernan stopped the rover near Van Serg and got off, he noticed that the rear edge of the taped maps had curled under as a result of the Sun warping their clear plastic coating. Cernan reported battery temperatures of 122 degrees and off-scale low, with forward drive motors at 210 and 240 degrees and rear drive motors at 225 and 220. The High-Gain Antenna was aligned once again and the TV camera turned on.

Schmitt got off the rover and walked over to the edge of Van Serg, describing the interior of the crater as being covered with dark, friable polymict breccias, created during the impact that formed the crater. He believed he would discover basalt blocks, but closer inspection revealed them to be breccias. He also thought there would be evidence of volcanism but none of the samples he looked at displayed this characteristic. They took their requisite rock and soil samples and photographs and, while doing a radial sample away from the rim of Van Serg, Schmitt discovered white soil several centimeters below the surface. Like all the small lunar samples, this was carefully bagged and identified by number. Houston at first wanted them to complete their tasks and return to the LM but then decided, at the request of the science Backroom, to take a core tube sample. Cernan assembled the core tube and then drove it into the lunar surface with his hammer. After driving it to the necessary depth, he extracted it, separated the tube sections and capped them. They then changed film magazines and removed the data recorder from the non-functioning

Surface Experiments Package receiver, which had failed from overheating. One of the final tasks was to deploy another seismic charge, and by this time Cernan and Schmitt had spent nearly an hour at Station 9.

The era of lunar exploration draws to a close

Parker informed them that the scheduled Station 10 stop at Emory and Sherlock craters was being scrubbed, and that they were to return to the LM. Parker then told them that Houston wanted an LRV sample 1.1 km from their last stop, which Schmitt collected. Several hundred meters from the LM, Cernan stopped the rover again for Schmitt to deploy another seismic charge. Schmitt discovered that the Lunar Hand Tool Carrier had unlatched from the Aft Pallet Assembly and swung open. The sample rake and scoop were missing, having fallen off sometime during the traverse from Station 9. Fortunately, the big sample bag was still firmly attached. Schmitt placed the seismic charge in a small depression, took a locator photo and rejoined Cernan on the rover. He then asked Cernan to drive toward a big rock he had up-ended earlier so that he could spot it and collect it as a sample at the end of their EVA. It was amazingly dark, nearly black. Schmitt placed it in the large sample bag at the rear of the rover and chose to walk the short distance back to the LM. Cernan parked the rover near *Challenger*, aligned the High-Gain Antenna again and turned on the TV camera so that Houston could watch their closeout activities. In total, Cernan and Schmitt had driven 36 km during their mission at Taurus-Littrow. Except for the damaged right rear fender and the failure of the battery temperature sensor, their rover had performed remarkably in some of the most rugged lunar terrain encountered during the J-missions.

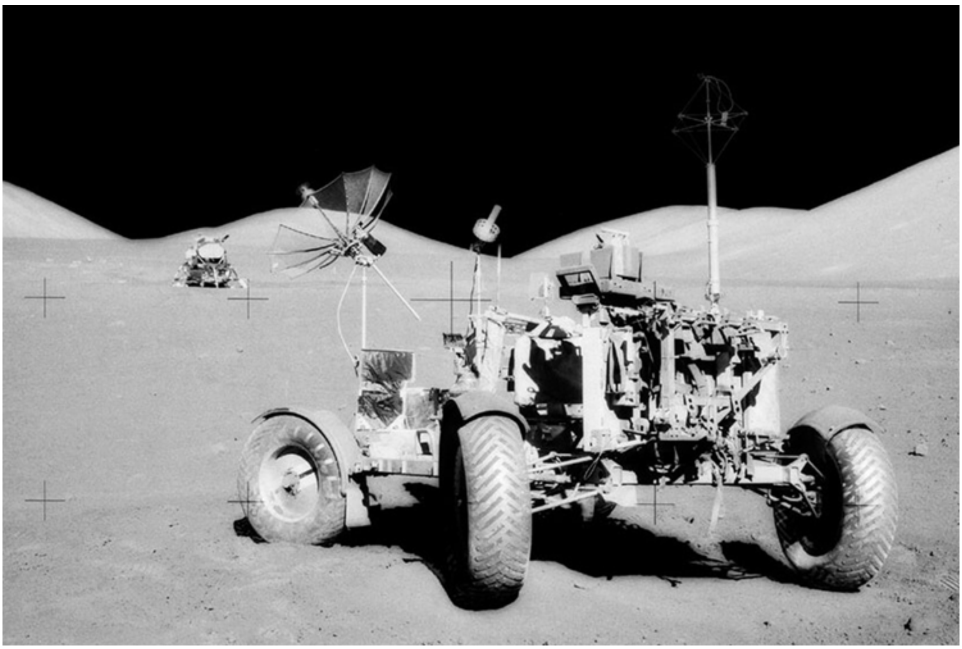
"The rover allowed us to explore the entirety of this valley of which I spoke," Cernan stated during the author's interview with him, "literally from one end to the other, North to South, to climb up hills we never would have been able to climb up on foot. It just would have been too tiring and too difficult. It's very tough on the surface. You can't really judge inclines and distances and sizes very well, and the rover allowed us to cover this entire valley from both a scientific and a geologic point of view, bring back samples and get pictures from places we never would have been able to get them from. We never would have been able to *get* to these places, I think that's the most significant thing about the rover. It was just so versatile and gave us so much additional advantage within the time frame that we had on the Moon, that without it, you could have cut down our science and geologic exploration by about seventy per cent. I don't think we could have gotten thirty per cent done of what we eventually did get done, without the rover. It was just a phenomenal asset."

After all the samples and core tubes were in the necessary sample collection bags and rock boxes, Cernan made a stirring address to many young students who were in Houston. Then he uncovered a curved plaque on the leg of the LM near the ladder, commemorating the mission of Apollo 17. He gave a moving dedication with the closing words: "This is our commemoration that will be here until someone like us, until some of you who are out there, who are the promise of the future, come back to read it again and to further the exploration and the meaning of Apollo."

Schmitt went out to the ALSEP site to perform some adjustments to the

equipment and some related tasks. Cernan got on the rover to drive it out a specified distance from the LM, known as the VIP Site, and positioned it so that Ed Fendell could issue commands from Earth for the TV camera to catch the liftoff of the crew the following day. The LRV dust covers were opened for the last time so that the batteries could cool down as they provided power for operation of the LCRU and TV camera. Cernan had removed the three good fender extensions and the expedient fender repair made of the taped maps and these were later brought aboard the LM to be returned to Earth. These would eventually find their way to displays at the Kansas Cosmosphere and the Smithsonian Museum. Cernan then aligned the TV antenna with its bore sight and confirmed the picture with Houston, at which point Ed Fendell then informed Parker that Cernan had parked the rover too close to the LM. Cernan got back on the rover and drove it a short distance further and for a brief moment, Houston received the only on-board TV images of Cernan driving the rover, since the TV camera was pointed toward him. He parked it once more and realigned the antenna toward Earth, then dusted the LRV for the last time and checked the TV lens to see that it was free of dust. Houston concurred. He then collected Schmitt's camera from under the seat.

"Okay. Let me get one parting shot [of] one of the finest running little machines I've ever had the pleasure to drive." Cernan went to the rear of the rover and took a



Eugene Cernan parked LRV-3 about 100 meters east of *Challenger* at the completion of EVA-3. The damaged right rear fender extension, maps and clamps and intact left rear fender extension were removed from the rover and brought back to Earth. Cernan had driven the LRV more than 30 kilometers on the Moon. (NASA)

photo of LRV-3's resting place, with *Challenger* in the distance. Beyond were some of the impressive massifs and hills they had explored, with the utter blackness of space beyond. Cernan and Schmitt finished the remainder of their tasks to close out their last EVA. Before re-entering the LM, they thoroughly dusted each other off, but were not completely satisfied with the result. Schmitt climbed the LM's ladder and Cernan passed up the sample collection bags, the Equipment Transfer Bag with their cameras, the fender extensions (including the improvised one), and the neutron flux probe from the deep drill core hole taken during this EVA. Schmitt transferred everything into the LM's cabin and Cernan climbed up the ladder, paused to look around, then looked toward the Earth and entered the LM. He closed and locked the LM's hatch and initiated cabin pressurization. They spent the next four-and-a-half hours preparing for the last sleep period on the Moon and liftoff the following day.

RETURNING HOME

"Challenger, Houston. We've got you on television now. We have a good picture," CapCom Gordon Fullerton reported to the crew shortly before liftoff from Taurus-Littrow on 14 December 1972. The TV camera was trained the on the LM.

"Glad to see old Rover's still working," Cernan replied with a hint of relief. The liftoff from the surface of the Moon took place at 188 hours, 1 minute and 39 seconds GET. Ed Fendell had punched in the command to start the TV camera's upward pan two seconds before liftoff and the camera panned precisely as *Challenger* left its descent stage behind on its way to lunar orbit. The ascent burn lasted 7 minutes and 18 seconds, putting them into the planned elliptical orbit. Cernan later used the Reaction Control System to adjust the orbit to put them on a rendezvous trajectory with Ron Evans in *America*. Once they rendezvoused with the Command Module, they transferred soil and rock samples and other items to the CM, then transferred all unnecessary equipment and supplies to the LM's cabin. The hatch between the LM and the CM was sealed and *Challenger* was remotely undocked from *America* and sent on an orbital path that would send it back to the Moon. It would impact on the eastern face of the South Massif, where the previously located seismic recording monitors would record the effects of the impact. They spent a day in lunar orbit before initiating the Trans-Earth Injection burn that sent them out of the Moon's grip back toward their home planet. At 301 hours 51 minutes and 59 seconds, the Command Module *America* and its crew splashed down in the South Pacific within sight of the recovery ship, the aircraft carrier *Ticonderoga*. First the crew and then the CM were transferred to the carrier by helicopter. Apollo 17 had been a spectacular success.

THE END OF THE APOLLO ERA

The end of the Apollo missions to the Moon officially occurred at Mission Control in Houston. In a subdued yet moving few minutes, the voice of Apollo Control, Robert T. White, Sr. spoke the following words:

> "This is Apollo Control, with the helicopter safely on deck. The network controller Dave Young will hang the final plaque in the Apollo series on the upper wall of the control room here. And this circuit, known up until now as Gemini Control, then Apollo Control, will reappear as Skylab Control ... in the spring. This is Apollo Control out, at 305:25 Ground Elapsed Time."

The audible click as the circuit went silent hung in the air and the silence seemed to go on for minutes. Those in Mission Control sat at their consoles, unwilling or unable to get up. An era of manned space exploration had ended and it seemed anti-climactic. No one knew when man would ever again return to the Moon. Years of unremitting effort, unparalleled achievement and scientific discovery, nerve-wracking crises, human tragedy, and gratifying success had quietly come to an end.

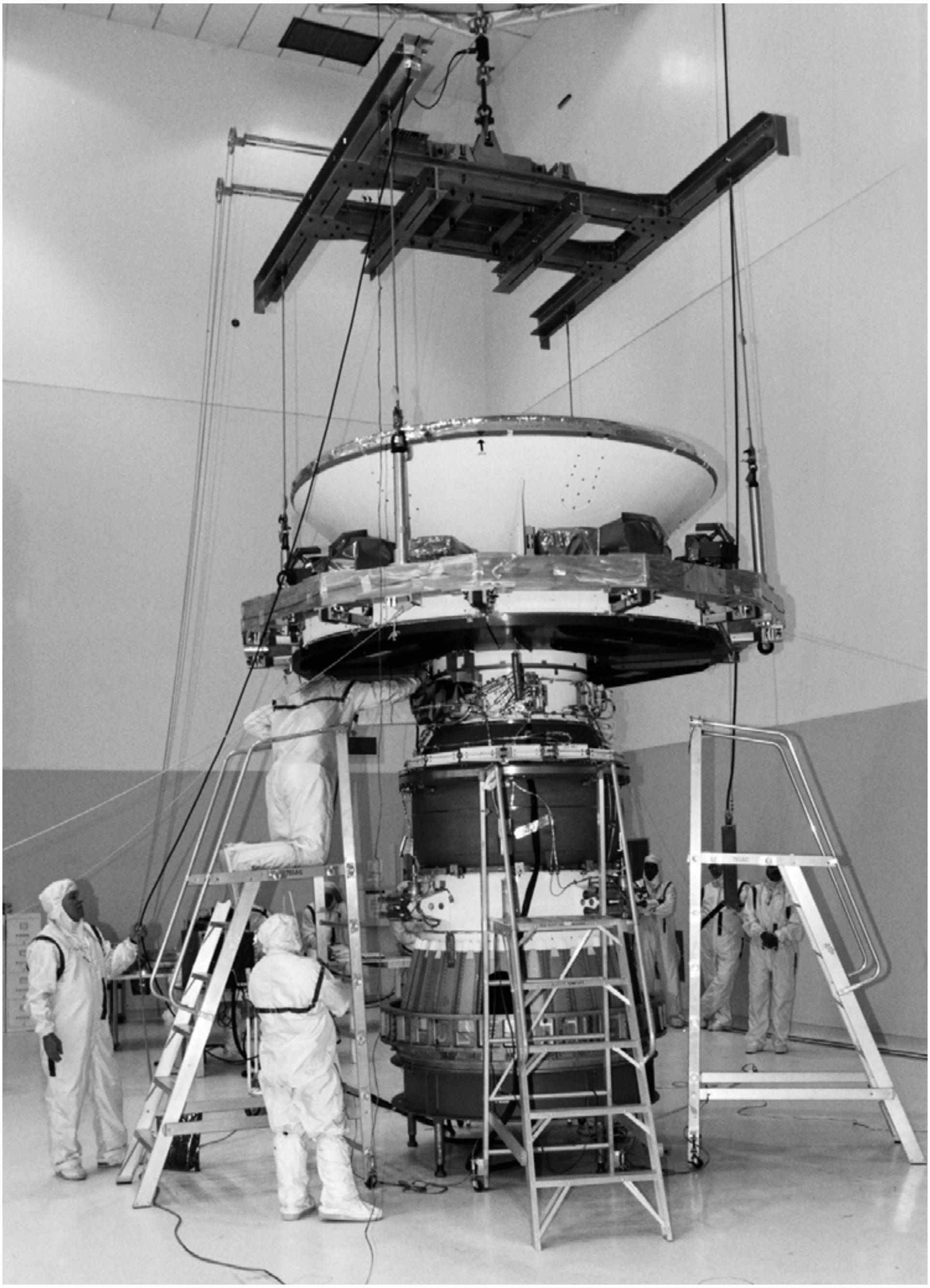
"When I left," Cernan recalled during this author's interview, "I remember climbing up that ladder, looking down into those sets of footprints, and since the Earth was, in our case, low on the horizon and for all the other flights it was overhead, it was just in our view all the time, particularly when I looked over my shoulder climbing up the ladder. There was the Earth, there were my footprints and I knew very well that I personally would not be back this way again, and that it might be some time before someone else would. But never in my entire life did I think it would be a generation. I thought we'd be on our way, not only back to the Moon, but on our way to Mars by the turn of the century. So it's a dubious honor to still be the last man to have left his footprints on the Moon at this point in time. But, my glass is not half empty, it's half full, because there are some young kids out there – a young boy or girl as I said in my book [*The Last Man on the Moon*, St. Martin's Press (1999)] – with the indomitable will and courage that is going to take us back out there where we belong. This increment in time will probably be a hiccup in history because there is no question that we are going back and we are going to Mars."

The quest for Mars

When the Apollo 17 capsule, *America,* splashed down in the Pacific Ocean returning its crew safely to Earth, it marked the end of American lunar exploration in the twentieth century. A new era was already underway, a very long era in which man would not venture beyond low-Earth orbit. The first of the new missions included Skylab, America's first long-duration space station. This was followed by the Apollo-Soyuz Test Project in 1975, the joint United States and Soviet Union mission to rendezvous an Apollo Command and Service Module with a Soyuz spacecraft. However, even as Project Apollo was within one year of achieving its goal of landing a man on the Moon, NASA had initiated a complex and expensive unmanned probe program to Mars. In 1968, NASA directed the Langley Research Center in Hampton, Virginia to begin work on a sophisticated spacecraft that would be launched toward Mars, orbit the planet in search of acceptable landing sites, and then soft-land on the Martian surface. This was Project Viking. The Viking spacecraft would be equipped to take photographs and beam them back to Earth, and the lander would carry instruments to study chemical composition, biology, magnetic properties, meteorology and other scientific functions, as well as take photographs of the surrounding area for relaying back to Earth.

THE VIKING MISSIONS

The Viking spacecraft was made up of an orbiter and a lander. Langley awarded development of the orbiter to the Jet Propulsion Laboratory in Pasadena, California, which would also be responsible for tracking and data acquisition and its Mission Control and Computing Center. Martin Marietta Aerospace in Denver, Colorado was awarded the contract to engineer and build the lander. Two Viking spacecraft would be built and NASA assigned its Lewis Research Center to procure and configure the Titan-Centaur launch vehicles for each spacecraft. This program had the luxury of more than six years of research, design, development, testing and finally construction, and it had a budget to match. Nevertheless, there were breathtaking cost overruns with project Viking, with the final program cost



The Mars Pathfinder spacecraft is shown being mated to its third stage in the SAFE-2 building at Kennedy Space Center. Inside was the micro-rover Sojourner. Pathfinder was launched aboard a Boeing Delta rocket on 4 December 1996. (NASA)

The Jet Propulsion Laboratory (JPL) in Pasadena, California has remained in the forefront of planetary exploration in general, and robotic exploration of Mars in particular, for decades. Its sophisticated facilities occupy 177 acres, managed by the California Institute of Technology for NASA. (NASA/JPL-Caltech)

estimated between at $700 million and nearly one billion dollars by the end of each mission.

Viking 1 was launched from Cape Canaveral Air Force Station on 20 August 1975, followed by Viking 2 on 9 September the same year. Viking 1 entered its Martian orbit on 19 June 1976 and spent one month imaging the Martian surface along its orbital plain, beaming its images back to Earth. The mission team selected Chryse Planitia as the landing site for Viking 1 and on 20 July, the lander separated from the orbiter and entered the planet's thin atmosphere, protected by its aeroshell and ablative heat shield. At 6 kilometers above the surface, the lander deployed its parachutes, the aeroshell was jettisoned, the lander's legs extended and finally the retrorockets slowed the spacecraft to a soft landing. Less than thirty seconds later, Viking 1 began transmitting its first photographic images from the Martian surface back to Earth and initiated its onboard experiments, starting its ninety-day mission.

Viking 2 began orbiting Mars on 7 August 1976. This time, the mission team selected Utopia Planitia, and Viking 2 landed there on 3 September. The images Viking 1 and Viking 2 beamed back to Earth were startling in their clarity and color,

and they remain remarkable considering the technology of the time, even to this day. Both spacecraft far exceeded their engineering operating lives. The Viking 2 orbiter ceased functioning on 25 July 1978, but the Viking 1 orbiter continued to operate and send back data until August 1980 when its attitude control fuel was finally expended. The last transmission from the Viking 2 lander reached Earth on 11 April 1980, while the Viking 1 lander sent its final transmission on 11 November 1982. The scientific and photographic return from project Viking was considerable. They were the first probes to successfully land on Mars (previous attempts by Russian probes had failed), but they were nevertheless immobile and it was the dream of more than a few mission planners at NASA that perhaps one day unmanned rovers could be sent to the Red Planet. However, it would be decades before a new generation of Martian probes would again explore its surface.

PATHFINDER AND *SOJOURNER*

The seeds of robotic rover development for the exploration of Mars by the United States were planted decades before the first of those rovers actually rolled onto the Martian surface. The Martian rovers that made NASA so proud and rekindled in the general public a new wave of interest in the Red Planet can trace their roots to the Surveyor Lunar Roving Vehicle (SLRV). The SLRV was built under contract for the Jet Propulsion Laboratory (JPL) by General Motors' Defense Research Laboratories (GMDRL) in Santa Barbara, California, under the direction of Dr. Mieczyslaw G. Bekker who was head of the Mobility Research Laboratory there. Bendix Corporation also participated in the program. The SLRV was, as the name indicated, a program to soft-land on the surface of the Moon and deploy a rover to survey possible landing sites for future manned Apollo missions. Demonstration tests of the prototype SLRVs were conducted by the U.S. Geologic Survey (USGS) for NASA, and at JPL's own test area near its facility known as the Arroyo Seco.

Early rover prototypes

However, the space agency decided to cancel the SLRV program, choosing instead to rely on the forthcoming Surveyor lander missions and photography from the Lunar Orbiter probes that were scheduled for their first mission in 1966. GM's SLRV was returned to JPL and went into storage, all but forgotten. More than ten years later, the SLRV was rediscovered and restored to functionality on a shoestring budget and the reborn project became a technology testbed. The first thing to be developed was a new vision system, employing stereo TV cameras to provide a 3-D view of terrain to monitors at a remote location. Next came Computer-Aided Remote Driving (CARD) and then "Semi-Autonomous Navigation." Several years of development work went into these new rover technologies and by 1986 the Blue Rover, as it was nick-named, was gaining attention at JPL. It was successfully able to navigate the rugged Arroyo Seco, near JPL. Refinements in these and related rover systems would come into play with the announcement, at JPL in the late 1980s, of the Mars Rover Sample Return (MRSR) program. The centerpiece of the research at

the time was to be the Pathfinder Planetary Rover Navigation Testbed vehicle, unofficially known as Robby. This vehicle would not be designed to explore Mars, but to prove the necessary hardware and technologies that would make such rovers successfully operate on Mars. JPL brought its best and brightest to the program, drafting in engineers who specialized in mechanical design, electrical power, thermal control, telecommunications and electronics, as well as software programmers and even orbital mechanics planners. All this was being done under the umbrella of the bigger MRSR program. The purpose behind this mission was to send a lander and rover to Mars. The rover would be deployed to collect samples, selecting the most interesting samples after returning them to the lander and loading them into a return launcher that would bring them back to Earth for study.

The Blue Rover and Robby were testbeds for evolving technologies, but their size and weight precluded anything of similar specification actually being launched to Mars. Much smaller rovers would have to be developed and behind the scenes, this was already happening. A rover is nothing if it does not have mobility, and with a much smaller vehicle size, the suspension design was quite a challenge. Dr. Bekker had done much pioneering work in this respect, but his vehicle designs were always quite large. One of JPL's design engineers, Don Bickler, devoted years to developing and refining the necessary suspension design that would permit a rover to surmount virtually all potential obstacles while remaining stable. Bickler did much of this development on his own time, after work, building prototype micro rovers in his garage. He made a discovery with respect to six-wheeled vehicle suspension design, and with refinement, this became identified as the rocker-bogie. The first of the prototype rovers employing the rocker-bogie suspension design was named Rocky. It was the first of a generation of rovers that would be built at JPL to validate this suspension design, as well as navigation capability, vision systems and the other technologies being explored. This suspension design was eventually patented by JPL, and would be employed on its future Martian rovers.

The Mars Rover Sample Return program proved too complex and expensive to continue and it was cancelled. Instead, there was a new push within NASA for smaller interplanetary and deep space exploration missions with smaller, fixed budgets, as part of the Discovery Program. In 1990, Dr. Wesley Huntress, director of NASA's Solar System Exploration Division (SSED), asked a scientific working group to propose specific missions that would fit the Discovery profile, as put forth by the Jet Propulsion Laboratory and the Johns Hopkins University Applied Physics Laboratory (JHU/APL). Among the first proposals was the Near-Earth Asteroid Rendezvous (NEAR), proposed by JHU/APL themselves. Also under consideration was JPL's Mars Environmental SURvey (MESUR) Pathfinder. Both missions received Congressional support and both would eventually be funded, along with follow-up missions in the Discovery manifest.

The Mars exploration and scientific community is an extremely diverse one, spreading from NASA Headquarters itself in Washington, D.C. to various NASA centers and affiliated universities across the United States, and including JPL in Pasadena, California. NASA's approach to program suggestion, consideration, evaluation and finally approval, is an arduous one – some would say positively

Darwinian. It is a process of evolution, adaptation and survival and even then, there is no guarantee that the program will see launch day. Nevertheless, with the support of Congress and under the direction of JPL, work began in earnest on developing new Martian missions under the Discovery umbrella.

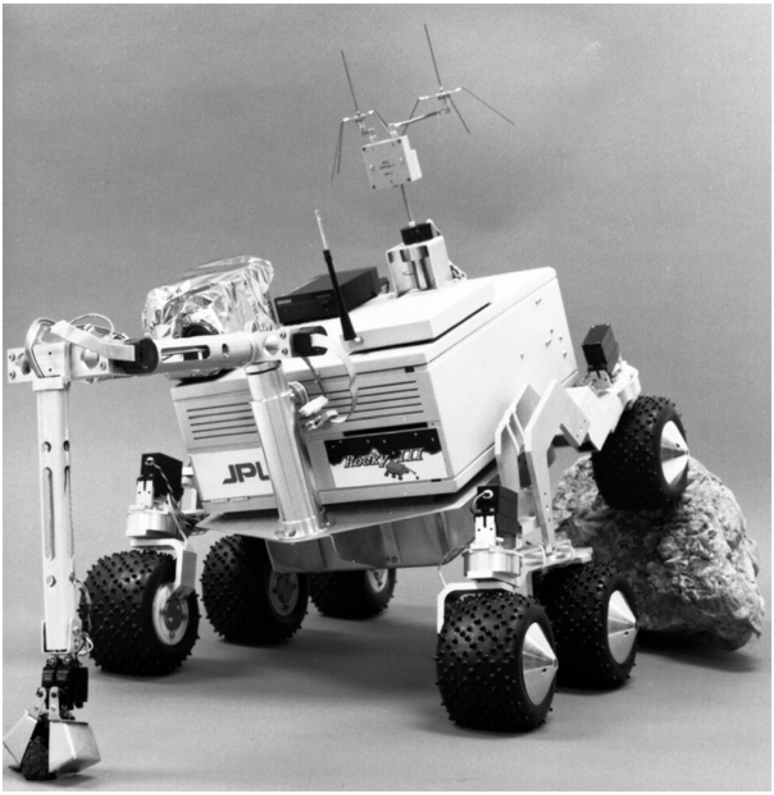
Rover designs evolve

A new phrase entered the JPL lexicon in the early 1990s: the Mars Science Microrover. The Rocky family slowly grew and by 1992, Rocky 4 was incorporating a rock chipper, seismometer and sensors, and displaying even better mobility. The next generation microrover, quite possibly the flight rover, would have to be solar powered, generating only a few watts of power. Thus, each electrical component would have to consume as little power as possible. The rover would also need to have a brain, and JPL selected the trusted Intel 80C85 microprocessor that had been reliably used on its space probes for years. It was slow, having only 6,500 transistors, but it could withstand the rigors of space radiation and could perform all the tasks required for this first Martian rover.

In the JPL world of space hardware design, however, everything is always subject to change. The design of the microrover was really in a state of flux, whether it involved the rover suspension and wheel design, thermal control, telecommunications design, power generation, or other systems. This was entirely new ground for the engineers at JPL, because it was one thing to design terrestrial rovers with little regard to either size or weight, but an entirely different thing to downsize the rover and all that entailed in order to fit on a lander that would take it to the surface of Mars. There were routine peer reviews of the rover design as it evolved and during the 1993 to 1994 timeframe, it became clear that the rover would have to have sufficient ground clearance during its short traverses, while at the same time being as compact as possible in order to fit on the folded lander. How could this be accomplished?

The solution was quite clever. The rocker-bogie suspension system was designed to be collapsible in relation to the rover body. Months of work went into this vital aspect of the microrover and when refined, it succeed in reducing the stowed height of the vehicle to only eighteen centimeters. Aside from this, an on-going debate continued as to whether the rover should operate with an electrical tether running to the lander, or whether the it should operate wirelessly. There were strong cases for and against each approach. The primary case for a tether was that it ensured uninterrupted communication and power from the lander to the rover. Against it was the very distinct possibility of the tether deployment spool somehow becoming jammed or the tether becoming snagged by a rock. In the end, the rover team succeeded in winning the vote for wireless communications. The rover would have onboard battery power, but they would not be rechargeable as this would add prohibitive weight to the vehicle. Instead, solar power would be the rover's primary electrical power source. By 1994, the flight rover program was given the name Microrover Flight Experiment (MFEX).

The rover and the lander were meant to be technology demonstrators. The mission to Mars was designed to prove capability through all aspects of the mission,



Robotic rover development at JPL began in earnest with the design of the rocker-bogie suspension system, resulting in the Rocky family of technology demonstration prototype rovers during the 1990s. Rocky III included a robotic sampling arm. (NASA/JPL-Caltech)

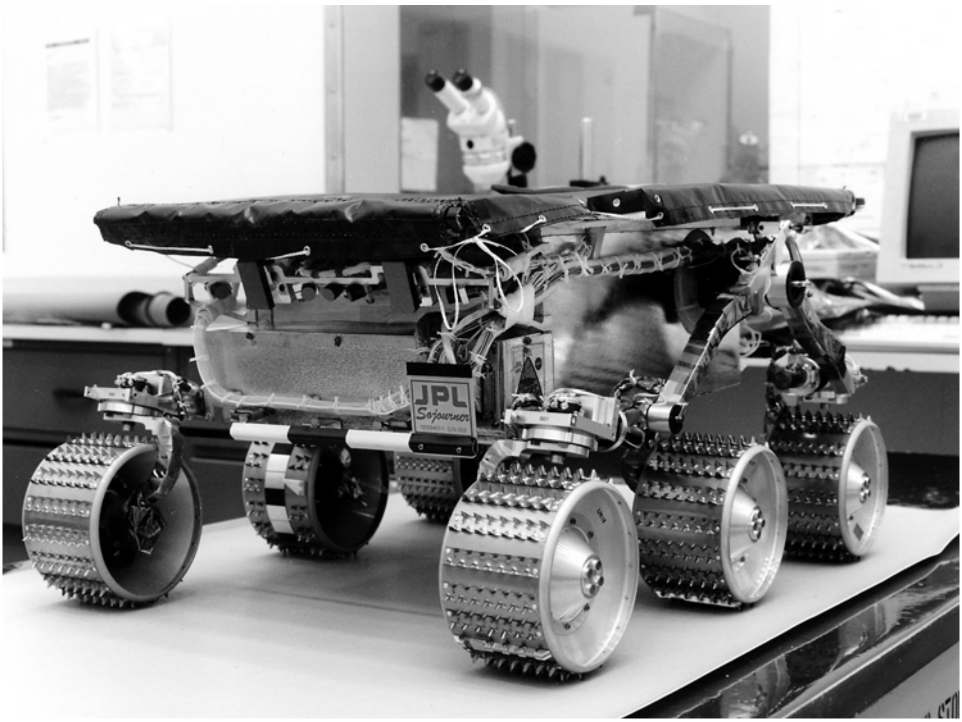
from launch, to entry into Mars' thin atmosphere, descent to its surface and deployment of the spacecraft once there. Any science would take a back seat. That did not sit too well with the scientific community, however, which saw this mission as a prime opportunity to gain new knowledge about Mars, something they had not been able to do for almost twenty years. However, MESUR Pathfinder was still regarded as a means to an end, a technology demonstrator that would prove many vital mission aspects that would be employed on future rover missions. Any scientific instruments on either the lander or the rover that jeopardized the fixed mission funding cap would be dispensed with.

"Pathfinder from beginning to end was a technology demonstration mission," Andrew Mishkin told this author in a 2006 interview. Mishkin was a Senior Systems Engineer on the program and would later work on the Mars Exploration Rover (MER) program. "It never became a science-driven mission. It was a cost-capped mission and was given the option of reduced capability in order to stay within that cost cap. That is one of the differences from a science-driven mission, where other

things would have to be rearranged to ensure that the original science objectives were met. This mission could be adapted and various capabilities altered in order to ensure that demonstration of the low-cost landing system could be achieved.'' [Mishkin's1997 book, *Sojourner: An Insider's View of the Mars Pathfinder Mission,* is listed in the Bibliography.]

Pathfinder and *Sojourner* design

The *Mars Pathfinder* program was an example of concurrent engineering under a pressing schedule and immovable budget. The whole spacecraft was, in fact, a series of complex systems, including the rover, the lander, the landing system and the cruise stage that would take the spacecraft to Mars after being launched aboard a Delta II rocket. Most of the *Mars Pathfinder* mission was cutting edge – it had never been done before. The landing system was a prime example. This mission would employ a unique (up to that point) system of heat shield entry, parachute deployment to slow the stowed spacecraft, backshell separation, lander separation and bridle deployment to distance the lander from the backshell, airbag landing system deployment, backshell retro rocket ignition to slow decent even further, and cutting of the bridle to permit the inflated airbag-protected lander to bounce across the landing site until



Sojourner was the first rover deployed on Mars as part of the Pathfinder mission. It was the first of NASA's Discovery missions conceived to lower and maintain planetary exploration program costs and development time. (NASA/JPL-Caltech)

coming to a stop. The airbags would be deflated, and the lander would right itself by deploying its petals, one of which held the rover. Practically every system had a series of nerve-wracking development problems that had to be resolved to get it to where it would perform reliably. It was no exaggeration to say that every engineer had to perform his specific tasks to near perfection for the entire mission to succeed.

The rover's electronics were perhaps the most sensitive to the temperature extremes that would be experienced during the Martian day (which is roughly 24 hours and 39 minutes long). Extra care had to be made to insulate the electronics without unduly adding weight to the vehicle and this proved particularly difficult for the engineers at JPL.

"One of the greatest challenges was designing the system to keep the electronics warm, and to do that with a small enough mass," Mishkin said. "The original design for what we called our Warm Electronics Box to contain the electronics, batteries and all, was designed to keep the electronics from cycling through such a high temperature range that it would eventually, through thermal expansion, start to cause components to fail. The design of that Warm Electronics Box was very challenging because the mass was just too great initially, and it took some very creative work by some people on the mechanical team to get to the notion of using solid silica aerogel to provide the insulation at a very low mass. That took over a kilogram out of the weight of the rover. For a vehicle that weighed only ten kilograms or so, that was a huge win."

Rocky 4 served as the development vehicle for the rover's systems, but two more critical vehicles would follow. The first was the System Integration Model (SIM). The SIM was practically identical in every way to the Flight Unit Rover (FUR), but the SIM would be the qualification unit that underwent all the necessary tests to validate the vehicle for the mission, much as the LRV Qualification Unit did for the flight unit LRV for Apollo 15, 16 and 17. Many of the tests planned for the SIM were much more severe than the pre-flight tests for the FUR or the actual conditions the rover would experience during the mission. A series of centrifuge tests of the SIM culminated in one with the centrifuge operating at 130 revolutions per minute, pushing the SIM to sixty-six times normal gravity – far more than the tests for the FUR. With all the results from the tests of the SIM correlated, work began on assembling the FUR. When it was finished it went through its own series of tests, as well as integration and further testing with the *Pathfinder* lander. JPL had conducted a contest during 1995 to name the future Martian rover, and the top two names selected were *Marie Curie* and *Sojourner*.

In mid-August 1996, the *Pathfinder* lander was carefully closed up, secured inside a protective shipping container, and trucked from Pasadena, California to the Kennedy Space Center in Florida. Two weeks later, *Sojourner* followed. It was secured in its own JPL-designed shipping container, nicknamed "the sarcophagus", which was then secured inside a commercial aircraft cargo container. This was delivered to the airport, where JPL engineers watched it being loaded on the jet bound for Orlando, Florida, before getting on the plane themselves. Arriving safely in Orlando, the rover's special shipping container was removed from the cargo container, loaded on a truck and driven to the Kennedy Space Center. For the next

several months, *Pathfinder* and *Sojourner* underwent testing and integration, before the lander containing the rover was finally closed up for the last time and the fully assembled spacecraft was mated to the Payload Assist Module (PAM-D) in the Spacecraft Assembly and Encapsulation Facility (SAFE-2) building at Kennedy Space Center. It was then placed inside the Delta II-7295 launch vehicle payload fairing on 21 November 1996.

On to Mars

The launch of *Mars Pathfinder* was scheduled for 2 December 1996 at 2:09 a.m. with a mere two-minute window in which to launch. The long-range forecast, however, did not look good, predicting high winds and rain, so the launch was scrubbed and rescheduled for 3 December at 2:03 a.m. The following day, JPL mission members returned to the most advantageous spot to watch the launch: Jetty Park across from Patrick Air Force Base. Just one minute before launch, a software problem in one of the ground computers monitoring telemetry from the Delta stopped the countdown. The problem could not be resolved in time and the launch was rescheduled yet again, this time for 4 December at 1:58 a.m. As the count passed the T-minus 30-second mark on this latest attempt, heart rates started climbing. Finally, the Delta II with *Mars Pathfinder* lifted off from launch pad C17-A. The exhaust plumes of the Delta's solid and liquid rocket engines were almost blinding as it rapidly climbed into the dark early morning sky over Cape Canaveral. Observers cheered and clapped, and soon the rocket was gone, on its way to Earth orbit. The Delta's PAM-D stage would then send it on its trajectory to Mars. Months of unremitting effort, stress and sometimes frustration gave way to tears as some JPL members openly cried in relief.

Pathfinder's destination was Ares Vallis, an ancient flood plain in the northern hemisphere of Mars. Despite being a technology demonstration mission, *Pathfinder* would still perform science once safely on the planet's surface.

"Ares Vallis is particularly interesting to geologists because it drains a region of ancient, heavily cratered terrain that dates back to early Martian history, similar in age to the meteorite Allan Hills 84001, which contains scientific evidence suggesting that life may have begun on Mars billions of years ago," said Dr. Matthew Golombek, Pathfinder Project Scientist, prior to the successful launch. "By examining rocks in this region, *Pathfinder* should [be able to] tell scientists about the early environment on Mars, which is important in evaluating the possibility that life could have begun there."

On 4 July 1997, the spacecraft performed the first series in a total of forty-one pyrotechnic events, and jettisoned its cruise stage. It entered the Martian atmosphere at more than 7,400 meters per second, at the start of its Entry, Descent and Landing (EDL) phase. Heat shield aerobraking would slow the spacecraft to roughly 400 meters per second before parachute deployment approximately eight to ten kilometers above the surface of Mars. This was the most anxious time for the engineers at JPL, but it was also being closely watched by each of the NASA centers around the country as well as NASA Headquarters. This was very much a high profile mission for NASA. Due to the distance between Mars and Earth, signals from the spacecraft would take more than ten minutes to reach the tracking and

A sophisticated airbag deployment system was developed by JPL to cushion the landing of Pathfinder and protect the spacecraft from boulders and rocks by bouncing and rolling across the surface of Mars until coming to a stop. The airbags were then deflated and retracted underneath the lander. (NASA/JPL-Caltech)

receiving stations, but finally, the tracking station in Madrid, Spain reported, "Comm, this is Madrid. I see a weak signal ..." All the EDL events had occurred perfectly. For a few brief seconds, there was pandemonium in the Mission Support Area (MSA) on the second floor of building 230 at JPL. Then, just as quickly, order returned as they waited for the next critical signals. The tetrahedral airbag system had actually come to a rest with the lander right side up – a one-in-four chance. The most dangerous part of the mission had passed. *Pathfinder* was on Mars!

Over the next several hours the airbags were deflated and retracted under the lander, and the lander's solar panels, or petals, were deployed. "We have lockup!" it was announced in the MSA, indicating the first signals from the lander's Low-Gain Antenna. Cheers went up. "We have rover data!" elicited more cheers. The mission

was already going better than many had dared to hope, but there was much yet to happen for the next technology demonstrations to occur. Data came in indicating that the tilt of the lander was only two degrees, a very positive sign that deploying the rover *Sojourner* would be that much easier. Another critical milestone was the alignment of the High-Gain Antenna with Earth. The Imager for Mars Pathfinder (IMP) had to properly locate the Sun and lock onto our solar system's star in order for the High-Gain Antenna to properly position itself toward Earth. Without this antenna, data and images would have to be transmitted through the Low-Gain Antenna at drastically reduced bit rates, diminishing the scientific return and health data of the lander and rover. The IMP locked onto the Sun then moved to survey the landing site, the High-Gain Antenna reoriented itself toward Earth, and the first images from the spacecraft started to appear on JPL monitors. The atmosphere inside the MSA was positively electric. All eyes were on the monitors as each image appeared. The Imager had a narrow field of view, and over the next several hours, JPL received images which were then digitally pieced together to form a mosaic. This included a panorama to determine the extent of airbag retraction, images of each end of the lander to determine the best direction for *Sojourner's* deployment, and an image of the area near the lander, the horizon and the Martian sky.

Examination of the images determined that the airbags had not retracted sufficiently to permit proper deployment of the rover's ramps. This had been anticipated, however, and a program was sent up to the lander to lift the petal with the rover approximately 40 degrees, activate the airbag retraction mechanism again and lower the petal. When the next group of images was received, the effort had proved successful, but all was not well. The lander was not communicating with the rover. All communications to and from the rover were done through the lander and if this problem could not be resolved, there would be virtually no mission on the surface. Until there were full communications between the rover and the lander, *Sojourner* could not be deployed.

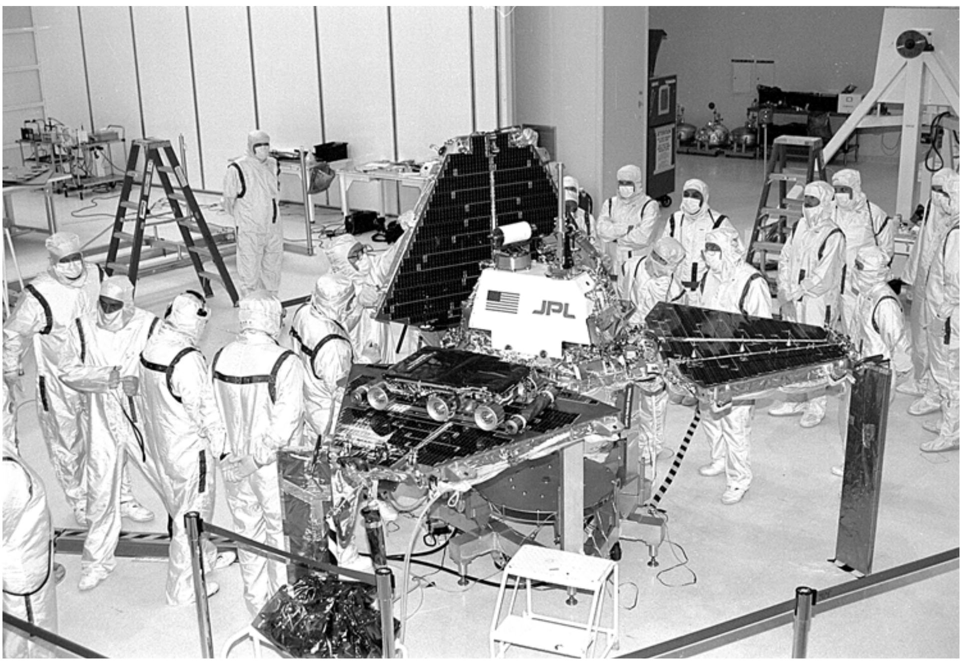
Over the next twelve hours, communication between the rover and lander was reestablished, and rover deployment was set for the next Martian day (known as a sol). Over the next seven sols, *Sojourner* would perform a number of technology experiments to gain information that could be applied to future planetary rovers. This included terrain geometry reconstruction from lander and rover imaging, basic soil mechanics by studying the degree of sinkage of each rover wheel, path reconstruction by dead reckoning and track images, vision sensor performance, and rover thermal characteristics between the Martian day and night. In addition, the rover would conduct a series of experiments to validate technologies for an autonomous mobile vehicle, employ its Alpha Proton X-ray Spectrometer (APXS), and image the lander as part of the engineering assessment after landing. It would have a nominal seven-sol mission. If it continued to perform well, the rover's mission would be extended.

First wheels on Martian soil

On sol 2, the command was sent to extend *Sojourner* to its full height and release its wheels from the lander. Drawing power from its 0.25 square meter solar panel and responding to commands from JPL, the rover drove down the ramp onto the

Martian surface at 05:40 Universal Time (UT). The first thing the rover did was to lower its APXS to the red soil for its first analysis. *Sojourner's* deployment onto the Martian surface, put together from a series of still images, was already being patched to networks and would become the top story for newscasts around the world. Images from the area around the lander were used to select the activities for the rover on sol three. At the Experiment Operations Working Group planning meeting for the next sol's events, the images displayed a nearby rock that would be the target of *Sojourner's* efforts.

Discussions had gone on at JPL regarding the identification of surface features during the mission. The only restriction issued by Dr. Golombek was that no names of actual individuals, either living or dead, could be used, so the target rock for sol 3 was thus identified as Barnacle Bill. The rover team was by now also gaining experience in ''driving'' the rover, traveling at one centimeter per second, giving them plenty of opportunities to study other potential targets. By the end of sol five, *Sojourner* had achieved its primary mission goals, two days ahead of schedule. It also returned a superb image of the *Pathfinder* lander. The health of the rover and the lander were excellent, and the mission now went into ''overtime,'' officially known as the extended mission. The public fascination with the *Mars Pathfinder* mission was overwhelming, as the JPL website that gave mission status reports and images from the lander and rover experienced nearly fifty million hits in its first week.



Sojourner, in its stowed position, was secured to one of Pathfinder's solar panels. White room conditions were essential during all aspects of the spacecraft's preparation and closeout prior to launch. (NASA/JPL-Caltech)

The rover visited other rocks or areas of intriguing soil over the following two weeks, among them Yogi, Scooby Doo and Cabbage Patch. As whimsical as the names were, the rocks and soil held a treasure trove of much desired knowledge of Mars and its history. Images from the lander's IMP and the rover's APXS were confirming the predicted findings for this region of Mars. On sol thirty-five, *Sojourner* headed for a dense rock field dubbed The Rock Garden. The APXS was brought to bear on rocks named Moe, Stimpy, Half Dome and Shark, among others. The rover also sent back close-up images of these rocks. It was clear by now how these rocks had been deposited on the Ares Vallis plain. On the *Mars Pathfinder* website, the scientific team stated:

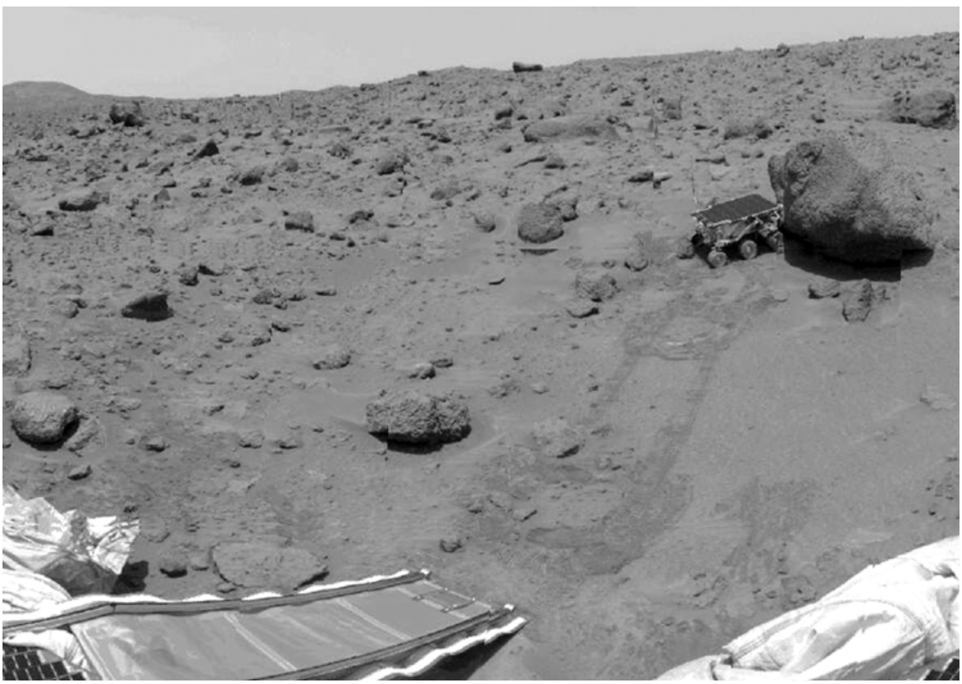
"The mosaic of the landscape constructed from the first images revealed a rocky plain (about twenty per cent of which was covered by rocks) that appears to have been deposited and shaped by catastrophic floods. This was what we had predicted based on remote-sensing data and the location of the landing site (19.13 degrees north, 33.22 degrees west), which is downstream from the mouth of Ares Vallis in the low area known as Chryse Planitia. In Viking orbiter images, the area appears analogous to the Channeled Scabland in eastern and central Washington state. This analogy suggests that Ares Vallis formed when roughly the same volume of water as in the Great Lakes (hundreds of cubic kilometers) was catastrophically released, carving the observed channel in a few weeks. The density of impact craters in the region indicates that it formed at an intermediate time in Mars's history, somewhere between 1.8 and 3.5 billion years ago. The *Pathfinder* images support this interpretation. They show semi-rounded pebbles, cobbles and boulders similar to those deposited by terrestrial catastrophic floods. Rocks in what we dubbed the Rock Garden – a collection of rocks to the southwest of the lander – are inclined and stacked, as if deposited by rapidly flowing water. Large rocks in the images (0.5 meters or larger) are flat-topped and often perched, also consistent with deposition by a flood."

The *Pathfinder* lander had a combined solar array from its three petals of 2.8 square meters, with rechargeable silver-zinc batteries. The rover ran essentially on its solar panel but had lithium thionol-chloride D-cell batteries as backup and auxiliary power. On sol fifty-six, its batteries ceased giving power, so the little rover could now only function during the Martian "day." Data from the lander's batteries showed their capacity was also slowly deteriorating. "Martian Time" as it was referred to, was also having a debilitating effect on the small team of rover "drivers", the engineers who commanded *Sojourner*. Over a period of two months, the engineers had to report to JPL at always shifting times, to the point that their lives had no correlation to daytime and nighttime on Earth. It was fatiguing and tedious and some engineers simply forgot the scientific and space exploration history they were making. Andrew Mishkin had to remind himself of the significance of what the rover team had accomplished, and what the mission meant to him.

"I think the most gratifying results were in getting to see things that could not be seen from the lander," Mishkin stated. "For example, sand ripples behind rocks the lander could not see, and getting close-up views of cracked or shattered rock. My personal interest was mostly in the ability to vicariously explore."

As the mission passed its eightieth sol, it had become abundantly clear that the JPL team had engineered a very rugged lander and rover. Some, however, speculated just how long it could go on. Finally, on the eighty-fourth sol, 27 September 1997, the Mission Support Area lost contact with the lander. Repeated efforts to reestablish contact failed and JPL mission management declared the mission completed. Mars *Pathfinder* had returned 2.3 billion bits of information, which included over 16,500 images from the lander and 550 images from the rover. *Sojourner* had provided fifteen chemical analyses of rocks and soil. Perhaps just as impressive were the more than 750 million "hits" the JPL *Pathfinder* website had recorded during the previous three months. The mission had been a spectacular success and JPL commenced planning for the next generation of Mars rovers for even more ambitious missions.

The loss of *Pathfinder* and *Sojourner* was overshadowed by the arrival two weeks previously of the *Mars Global Surveyor* probe that was now circling the planet. This was a sophisticated orbiter that would take unprecedented images and perform remote sensing and mapping. The success of these two missions gave added momentum to those planned and already underway, but as history would prove, this was no guarantee that the next missions would succeed.



Pathfinder landed in the Ares Vallis region of Mars on 4 July 1997. Two days later, Sojourner drove down the ramp onto the Martian surface. Nominal mission length was seven Martian days, or sols, but Sojourner continued to operate successfully for more than 80 sols. (NASA/JPL-Caltech)

DISASTER STRIKES THE MARS EXPLORATION PROGRAM

On 23 September 1999, the *Mars Climate Orbiter* reached Mars and executed a 16 minute 23 second orbit insertion burn. It passed behind Mars at 09:06 UT, which was marked by the loss of signal. The ground tracking station should have reacquired the probe's signal at 09:27 UT, but no signal was ever received. Repeated efforts to establish contact failed and the mission was declared a loss. A review board determined that commands sent in English instead of metric units for a critical trajectory correction burn had resulted in the probe crashing onto the Martian surface. This was an embarrassing loss for the Jet Propulsion Laboratory, and of great concern because it had another probe already on its way to Mars. The *Mars Polar Lander*, with a pair of microprobes named *Scott* and *Amundsen*, entered the Martian atmosphere on 3 December 1999. The microprobes were to be released at high altitude, and were designed to penetrate the Martian surface and then begin to send back data. But the tracking station lost data from the *Mars Polar Lander*, and never received data from the microprobes. JPL spent a month trying to acquire a signal from the lander and the probes before declaring the mission a loss. A subsequent mission review determined that the lander's legs had issued spurious signals causing a premature shutdown of the descent engine, resulting in the destruction of the spacecraft. NASA and JPL had lost two space probes within the space of three months.

NASA Administrator Daniel S. Goldin appointed Thomas Young, a respected space industry executive, to form the Mars Program Independent Assessment Team (MPIAT), which would conduct a top-down review of the programs, management,

This image, taken on 14 July 1997 by Pathfinder, shows the rugged plain where it landed and the distinctive Twin Peaks in the distance. (NASA/IMP Team, JPL)

contractors and relevant issues and present its findings to NASA. In presenting the report in mid-March of 2000, Young emphasized the difficulty in successfully accomplishing such logistically and technologically challenging missions.

"One of the things we kept in mind during the course of our review was that in the conduct of space missions, you get only one strike, not three," Young explained. "Even if thousands of functions are carried out flawlessly, just one mistake can be catastrophic to a mission. Our review confirmed that mistakes can be prevented by applying experienced oversight, sufficient testing, and independent analysis." Key findings of the MPIAT report were:

- Mars exploration is an important national goal that should continue.
- Deep space exploration is inherently challenging, but the risks are manageable and acceptable.
- NASA, the Jet Propulsion Laboratory (JPL), and U.S. industry have the unique capabilities required to conduct successful planetary and deep space missions.
- NASA's "faster, better, cheaper" approach, properly applied, should be continued as an effective means of guiding program implementation.
- There were significant flaws in the formulation and execution of the Mars program, but all of the problems uncovered were correctable in a timely manner to allow a comprehensive Mars exploration program to continue successfully.

That comprehensive Mars exploration program had been under carefully reexamination, reorganization and rescheduling for months. One mission proposal involved the landing and deployment of a bigger and more sophisticated rover that carried all the scientific instruments with it. It had been a concept first put forth by Steve Squyers years before and had evolved as it competed with other lander and orbiter proposals submitted to NASA. Not only would NASA approve the rover proposal, it would ask JPL for two of them.

MARS EXPLORATION ROVERS *SPIRIT* AND *OPPORTUNITY*

On 10 August 2000, NASA announced its next Mars mission. It was actually two missions, each with separate rovers. The Mars Exploration Rover (MER) program would launch two highly sophisticated and autonomous rovers to Mars in 2003 to take advantage of the closest proximity of Mars to Earth in 60,000 years.

"For the past few weeks, NASA has been undertaking an extensive study of a two-lander option," announced Scott Hubbard, Mars program director at NASA Headquarters. "The scientific appeal of using the excellent launch opportunity in 2003 for two missions was weighed carefully against the resource requirements and schedule constraints. Our teams concluded that we can successfully develop and launch these identical packages to the Red Planet. We also determined that, in addition to the prospect of doubling our scientific return, this two-pronged approach adds resilience and robustness to our exploration program."

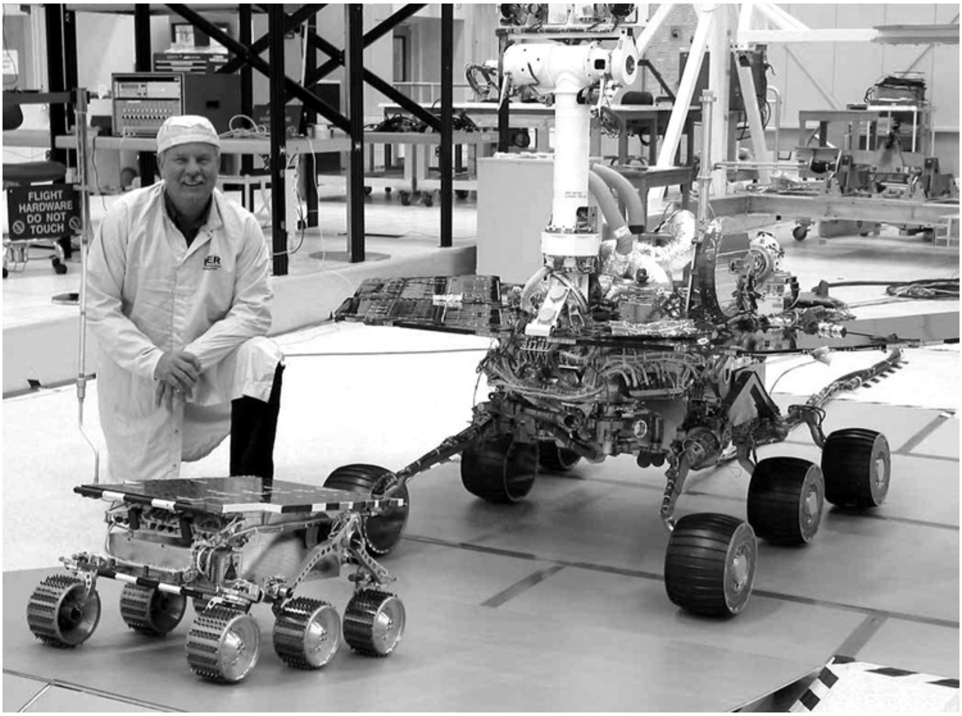
Whereas the *Mars Pathfinder* mission was a technology demonstration, the MER program would draw on that technology as intended, but would improve upon it with a vastly expanded science mission designed to return unprecedented images and scientific data about the discoveries these two rovers would make. The suite of scientific instruments included on the rovers had been proposed by Steve Squyers, a professor of astronomy at Cornell University. Squyers had, in fact, been proposing such a scientific package to go on a rover since 1995, but he had numerous scientific competitors also seeking a NASA mission to Mars. In keeping with the mythological names given to high profile programs like Mercury, Gemini and Apollo, Squyers selected *Athena* for his scientific payload, after the Greek goddess of wisdom, art, and war. He had been persistent, and he, and his team of scientists who wrote the proposal for a more elaborate Martian rover mission as part of NASA's Discovery program, finally succeeded in 2000. The Mars Exploration Rover missions would be far greater in scope and engineering difficulty, and would involve scientific partners from around the world.

Success under pressure

JPL was handed the task of engineering the rovers, landers and EDL systems, as well as planning the mission operations. Pete Theisinger, a JPL veteran whose experience went back to the Mariner program of 1967, would be the project manager. He assembled a team of the finest available JPL engineers to work on the MER program. Squyers would work with Theisinger's engineers to realize the *Athena* scientific payload that would go on the rovers. The rovers would be larger than *Sojourner* and bear little resemblance to the microrover, but it was believed that the *Pathfinder* EDL system and lander could be used with little modification, though the mass of the eventual rover would prove otherwise. The problems that the MER program would encounter could not be foreseen, but no additional time could be given to the program to resolve them. The rovers had to be launched in a given window of time only several weeks long, or they would have to wait another twenty-six months before trying again – an unlikely possibility. Most daunting was the fact that three years was an alarmingly short time span to engineer, build, test, validate, deliver and launch two sophisticated and complex spacecraft on two different missions.

"The primary resource constraint on MER was time," Mishkin recalled. "Basically, the rule is that the planets don't wait. You can only launch to Mars at certain times. The MER mission started up with less time than we would have liked. There was a transition from *Pathfinder* to MER, actually from a relatively small team to a much larger team, but even so, the team had to work even harder than the *Pathfinder* team had due to the schedule constraints. The resources were there but the time pressure was extreme and it did require many people to work sustained periods of many long hours."

In the face of this challenge, JPL did have some things working in its favor regarding the MER. One of them was the *Athena* payload. This scientific payload had actually been developed for an earlier Mars mission, *Mars Surveyor 2001*. As a package for the *Surveyor* '01 rover mission, it included an Alpha Particle X-Ray



The difference in size and complexity between the first-generation Mars rover and the Mars Exploration Rover (MER) is evident in this photo. (NASA/JPL-Caltech)

Spectrometer (APXS), a Microscopic Imager, a Mini-Corer, a Mini-Thermal Emission Spectrometer (Mini-TES) and a Mossbauer Spectrometer. The rover was to be outfitted with Panoramic Cameras (Pancam) mounted on a mast at the front. All these technologies had matured to the hardware stage before the *Surveyor 2001* program was cancelled, but this development maturity of the *Athena* payload was one reason NASA had selected Squyers' proposal, and went a long way toward making the Mars Exploration Rover missions possible. For the new package, the Mini-Corer would be replaced by a Rock Abrasion Tool mounted on a robotic arm. Also mounted on the robotic arm would be the Microscopic Imager, the Alpha Particle X-ray Spectrometer and the Mossbauer Spectrometer.

The MER rover program had something else working in its favor. Since 1999, JPL had been conducting tests in the Mojave Desert with the Field Integrated Design and Operations testbed, known as FIDO. This vehicle was originally designed and built to test the systems needed in a rover as part of the Mars Sample Return mission. Even as a testbed, FIDO's capabilities were quite advanced.

"FIDO's advanced technology includes the ability to navigate over distances on its own and avoid natural obstacles without receiving directions from a controller," Dr. Eric Baumgartner stated in an April 1999 JPL press release. "The rover also uses a robot arm to manipulate science instruments and it has a new mini-corer or drill to

extract and cache rock samples. There are also several camera systems onboard that allow the rover to collect science and navigation images by remote-control."

"FIDO is about six times the size of *Sojourner* and is far more capable of performing jobs without frequent human help," Dr. Paul S. Schnenker, who was in charge of FIDO's development at JPL, stated in the press release. "FIDO navigates continuously using on-board computer vision and autonomous controls, and has similar capabilities for eye-to-hand coordination of its robotic science arm and mast. The rover has six wheels that are all independently steered and can drive forward or backward, allowing FIDO to turn or back up with the use of its rear-mounted cameras."

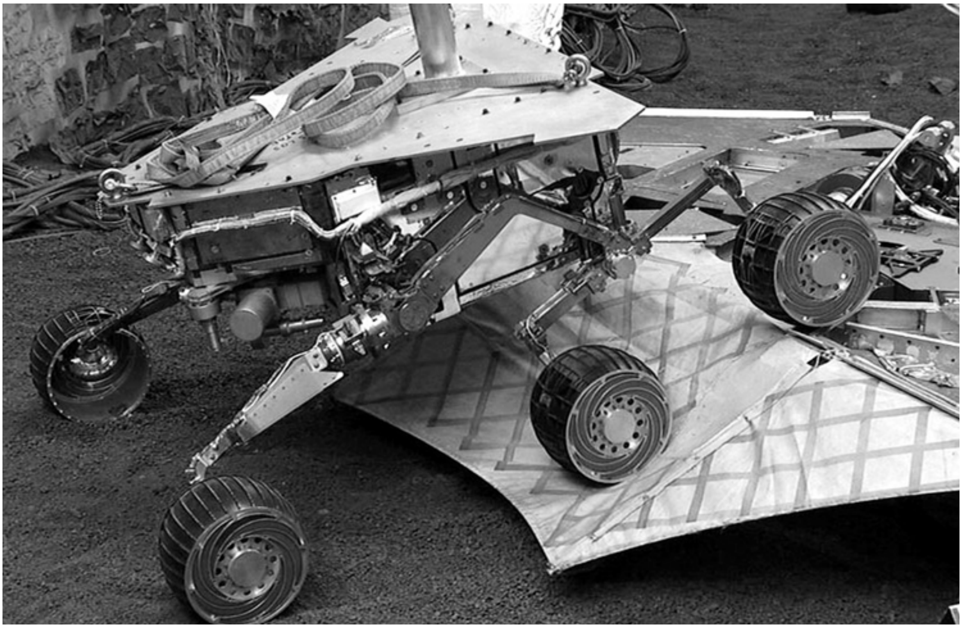
When the Mars Sample Return mission was cancelled, FIDO was called upon to contribute to the development of the Mars Exploration Rovers. Many of the technologies developed for FIDO would find their way into the MER rovers, but there were still critical issues of size and weight. There was a MER preliminary design review in October 2000, and it was clear that the new rover could not fit on the lander as designed for *Pathfinder*. The lander would have to get bigger, even as the design for the rover was evolving. The main elements of the rover's evolving design, apart from the *Athena* scientific package, were the rover's Warm Electronics Box, the wheels and rocker-bogie suspension, and the all-important solar arrays.

MER from the ground up and inside out

The solar arrays were a critical item, because the rover needed all the electrical power it could get. The larger the arrays, the more power the rover would have. However, there were limits to the size of the arrays, both to fit inside the lander's tri-pyramid envelope and to keep the rover's weight down as much as possible. Mechanical Lead for the Mars Exploration Rover was Randy Lindemann and of all the systems he was responsible for on the MER, the solar arrays would be the most problematic – in terms of struggling to find a suitable design that provided the needed power while fitting into such a compact envelope. Lindemann and his engineers spent months working out the packaging problem of laying out the photovoltaic cells in groups called strings, arranging them on the rover's panels, and experimenting with different designs for the solar array panels to unfold from the rover. The finished design met the rover's power requirements and packaging constraints and the opened panels, measuring a total of 1.3 square meters, gave the MER rover a swept-wing look.

The rover's core structure employed composite honeycomb panels with the interior insulated with silica aerogel, the same amazing material used inside *Sojourner*. The Warm Electronics Box would keep the rover's vital electrical and electronic components warm through the use of eight radioisotope heater units, electrical heaters and heat given off by the components themselves. The rover's computer would employ a Rad 6000 32-bit micro-processor, a radiation-hardened version of the commercial product. The Rad 6000 was capable of twenty million instructions per second, with the rover's computer running the VxWorks operating system. The computer had 128 megabytes of memory (RAM), but was backed up by 256 megabytes of flash memory.

The two cognizant engineers responsible for The MER rovers' mobility system were Chris Voorhees and Brian Harrington. This system included the wheels, drive



A MER testbed performs an egress test at JPL's In-Situ Instruments Laboratory. (NASA/JPL)

and steering actuators and rocker-bogie suspension. The sophistication and capability of the MER rover mobility system was as challenging to engineer as the solar panels. The components were designed in concert with each other and with elements of the lander (and even the airbag system), and they evolved as the rest of the rover and lander evolved. The wheels were an example of this evolutionary process.

"We started with the *Sojourner* wheels as a base to work from," Voorhees said. "Because of many different engineering demands on the wheels, the wheels for our new rovers didn't mature until late in the game. A big challenge was to be able to get enough traction to get through soil and over rocks but also to be benign enough to get off the lander without getting entangled in the deflated airbags."

Like virtually every other part in the MER rover, the complex wheel was designed with 3-D modeling software and evaluated with finite element analysis software in order to make the wheel as light as possible while being strong and flexible. The wheel's hub featured spiral flexures which gave the wheel necessary shock-absorbing capability. The flexures were filled with Solimide, an open-cell foam that retained its flexibility even in the temperatures encountered on Mars. This was done to protect the drive and steering actuators inside the wheel. The twenty-six-centimeter-diameter wheels were curved along their entire circumferential surface to maintain uniform contact with the Martian soil throughout its total steering geometry. Each wheel was not an assembly, but was machined entirely from a single, solid billet of aluminum. The wheel design went through numerous iterations that changed as a result of testing and subsequent improvement.

The rocker-bogie suspension system was designed so that when one side of the rover's suspension moved upward upon reaching a large rock or obstruction, the suspension on the other side of the rover moved downward to keep the rover level. The two front wheels, drives and steering actuators were designed to pivot toward the center of the rover and stow, while the middle pair and rear pair of wheels were retractable to permit the rover to crouch on the lander for the lowest possible height and most compact envelope. The front and rear wheels also all had individual steering actuators and all six wheels had individual drives.

Rising above the rover's equipment deck was the Pancam Mast Assembly (PMA). This articulated mast supported both the Pancam and the Mini-TES. The Pancam included two digital cameras mounted within the camera bar, using Charged Coupled Devices (CCDs), with each camera having a small multi-spectral filter wheel. The Pancam would be capable of providing multi-spectral, stereoscopic and panoramic images, while the Mini-TES would provide remote sensing of soil and rock mineralogy. The optics of each camera used three-element symmetrical lenses, spaced thirty centimeters apart and 1.5 meters above the planet's surface. The optics and filters were protected from the Martian environment by a sapphire window in front of the optics barrel. The camera bar could pivot plus or minus ninety degrees in elevation, and the PMA could rotate 180 degrees in either direction for 360 degrees of coverage. The rover's navigation cameras (Navcams) were also mounted on the camera bar. The PMA would be erected from the stowed horizontal position to its vertical operating position by a deployment actuator at its base.

On the rover equipment deck behind the PMA were the High-Gain Antenna, the Low-Gain Antenna and the UHF Antenna. Both the High- and Low-Gain Antennas were capable of sending and receiving data utilizing the Deep Space Network on Earth. The High-Gain Antenna had the advantage of being able to precisely point to antennas on Earth and send data at much higher transmission rates. Through the UHF Antenna, the rovers could also uplink and downlink information initially with the orbiting satellite *Mars Odyssey* and, eventually, the *Mars Global Surveyor*. This approach was preferable because data could be transmitted to and from the orbiters faster, and the orbiters could remain in communication with Earth longer than the rovers.

The EDL system and lander

The lander and EDL systems had size and weight issues of their own. As originally proposed by engineers at JPL in April 2000, the "build-to-print" concept was to employ the *Mars Pathfinder* lander and EDL system for the Mars Exploration Rover, with perhaps fifty per cent of the launched dry mass inheriting detail design from the *Pathfinder* program. It didn't turn out that way. As the rover grew, the lander grew and virtually every component in the EDL system increased in size and weight. The cruise stage actually ended up weighing less than its initial mass estimate. The first tests of the MER airbag system with a dummy lander and rover were performed in the United States' largest vacuum chamber at NASA's Plum Brook facility at the Glenn Research Center in Sandusky, Ohio. The airbag system was made up of four, six-lobed tetrahedral airbag segments, each one mated to an

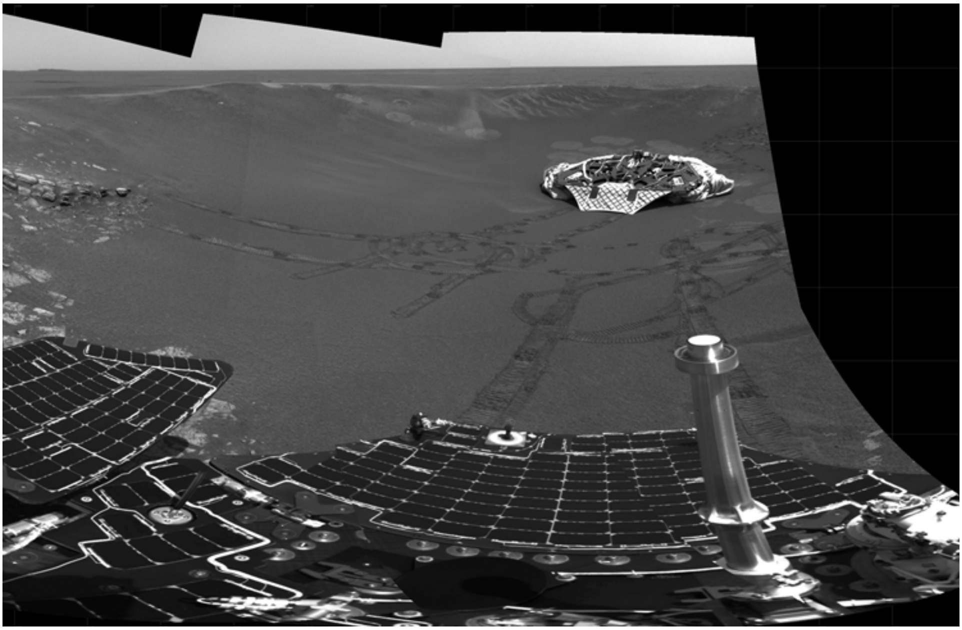
exterior lander surface. The airbags used an abrasion layer to prevent tearing of the inflated bags from inconveniently placed rocks on the sloped surface it would impact. This design had worked well with *Mars Pathfinder*, but the first test was a catastrophic failure, ripping through the abrasion layer and puncturing the inner bladder of the bags, surprising the test engineers.

JPL worked with the manufacturer of the airbag system, ILC Dover of Frederica, Delaware, over the next two-and-a-half years to redesign and strengthen the MER airbag system and confirmed the effectiveness of the changes with more tests (including deflation and retraction under the lander and its petals). JPL engineers also discovered that the greatest likelihood of airbag tearing took place when a lobe struck one of the sharp test rocks at an oblique angle when simulating being carried along by Martian wind during impact. Some method had to be developed to eliminate the horizontal velocity of the spacecraft with inflated airbags during the final seconds of descent, and JPL engineers devised a Descent Image Motion Estimation Subsystem (DIMES) to work with the Traverse Impulse Rocket Subsystem (TIRS) that would eliminate lateral movement during firing of the retro-rocket system. This would permit the lander to inflate its airbag system, cut the bridle and drop to the planet's surface and bounce more than fifteen times before coming to a stop.

The EDL parachute system development went through similar heart-stopping moments for the JPL team. *Mars Pathfinder* had employed a disc-gap-band parachute that featured a hemispherical main segment with an air gap and a band of parachute material designed to add stability during descent. The engineers knew the original parachute was too small to do the job, so the size of the parachute was increased. However, there were limits to what the size the parachute could be in order to fit into its cylindrical storage canister aboard the lander. The first parachute test took place at the National Guard Gunnery Range in Boise, Idaho in April 2002. To replicate the shock to the parachute system opening in the Martian atmosphere while traveling at hundreds of kilometers per hour, the weight of the dummy payload had to be increased to 3,600 kilograms. The first test resulted in a torn canopy and shredded band. A second test the following day produced the same result. With launch day now just over a year away, three new parachute designs were developed and were tested several months later at NASA's Ames Research Center wind tunnel. The first test parachute exhibited "squidding" where the chute failed to open completely. The chute was redesigned, then redesigned again before tests were finally successful.

In August 2002, JPL conducted new field tests with a FIDO that had received modifications to permit command, control and communications as planned for the MER missions. JPL issued a news release that described the scope and success of the field tests.

"The test rover has received and executed daily commands via satellite communications between JPL and the remote desert field site," Dr. Ed Tunstel stated in the news release. "Each day, they have sent images and science data to JPL that reveal properties of the desert geology."



The pictures taken by the MER rovers Spirit and Opportunity were digitally aligned to form a nearly seamless mosaic final image. This partial panoramic image was taken by Opportunity's navigation camera on sol 34. It shows the MER's lander in the center of a crater on Meridiani Planum. Note the circular impressions on the walls and floor of the craft from the inflated airbags. ((NASA/JPL)

Race to the Cape

The pieces of the MER puzzle were fitting into place. As with every program of such complexity, however, problems continued to arise and continued to be solved almost up to the time the spacecraft were on the launch pad in Florida. This critical phase was known as Assembly, Test and Launch Operations (ATLO). The Mars Exploration Rovers, landers, and cruise stages were assembled in JPL's famed Spacecraft Assembly Laboratory. The spacecraft's aeroshell, including the backshell and heat shield, would be supplied by Lockheed Martin Astronautics Company of Denver, Colorado. ATLO had been underway since 25 February 2002, and was under tremendous schedule pressure. Many JPL personnel secretly doubted that the spacecraft would get to Florida in time for the launch window in June 2003. To succeed sometimes required a twenty-four hour, seven-day-a-week multi-shift work schedule. The individual rovers were not yet named, instead being referred to as MER-A and MER-B. The first rover to complete its final tests was MER-B, and it left the Jet Propulsion Laboratory in the early morning hours of 22 February 2003, in a special cargo truck accompanied by other convoy vehicles, headed for Cape Canaveral Air Force Station in Florida. MER-A followed several weeks later.

The MER rovers were delivered to the Payload Hazardous Servicing Facility at the Cape. There, they would spend the remaining months of ATLO undergoing

further testing, integration with their landers, more testing, closing up each lander and securing them inside their aeroshells, and assembling the aeroshells to the cruise stages, before finally mounting the payload to the solid rocket motor third stage and then securing them inside the payload fairing of the Delta II rocket. Problems continued to plague the rovers and other equipment up to the final days before launch, but they were all overcome thanks to overwhelming dedication by all the members of the team.

NASA had held a contest to name the rovers, and the winning entry came from nine-year-old Sofi Collis from Arizona with a poem that included *Opportunity* and *Spirit*. On 10 June 2003, *Spirit* (MER-A) was launched at 17:59 UTC destined for Gusev Crater, named after the Russian astronomer Matvei Gusev. Located fifteen degrees south of Mars' equator, Gusev Crater was a shallow impact crater measuring roughly 150 kilometers in diameter. *Opportunity's* landing site was the Meridiani Planum halfway around the planet from Gusev. The MER team had succeeded in reaching the goal of launching the spacecraft on time, but at great personal sacrifice. Between the summer of 2002 and the launch of both rovers in mid-2003, the JPL team had been given only one two-day weekend off.

THE MARS EXPLORATION ROVERS BEGIN THEIR MISSION

On 3 January 2004, the spacecraft holding *Spirit* entered the Martian atmosphere and began its EDL phase. The spacecraft signals received by JPL confirmed that every critical phase of EDL was occurring precisely on time. When it was announced that they had received the signal that the airbag-protected rover and lander were bouncing on the Martian surface at Gusev Crater, the mission control room erupted in cheers and applause. Over the next several hours the airbags were deflated, the lander petals opened and locked and the rover's PMA deployed in preparation for sending the first images from *Spirit* back to Earth. When the first images were placed up on the displays, the room was once again filled with cheers and applause. This was a moment of excitement and wonder for all those present. *Spirit* would soon start its scientific mission of exploration.

The JPL team took its time getting *Spirit* ready for its mission. Each of the rover's scientific instruments and systems was carefully checked over the next several sols until, on 15 January, the commands were sent for *Spirit* to egress the lander. Twenty minutes later, JPL received the data that the rover had completed this successfully and was on the surface of Mars. Another mission milestone had been reached. The following sol, the robotic arm, formally known as the Instrument Deployment Device, was activated and extended and the first images with the microscopic imager were taken. The other instruments on the arm were checked in preparation for a close-up examination of a nearby rock. On 19 January, the rover approached a football-sized rock, named Adirondack. This was the first target of examination to employ the rock abrasion tool and the other instruments. As the rover was about to use the rock abrasion tool on the rock, the station in Canberra, Australia reported to JPL that it had not received confirmation from the rover to begin. Communication

On sol 175 (30 June 2004) Sprit took this image, with its front hazard avoidance camera, of the instrument deployment device inspecting a rock target named “Bread Basket”. The close-up image of the rock was captured by its microscopic imager. (NASA/JPL)

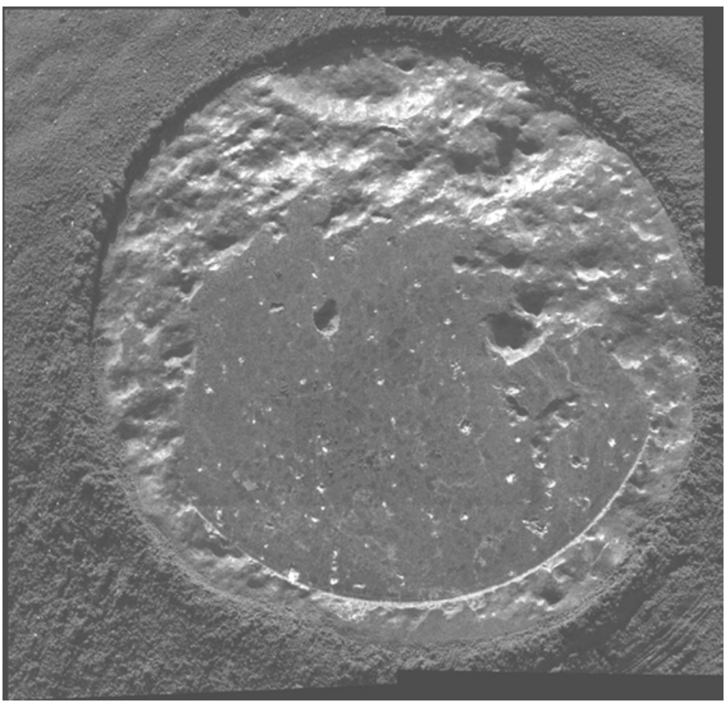
with *Spirit* had been lost. JPL worked around the clock over the next several days to determine the problem and work a solution to reestablish contact with the ailing rover.

As the *Spirit* mission team dealt with the rover’s communication blackout, the *Opportunity* team prepared for EDL on 25 January. The spacecraft successfully landed at Meridiani Planum and that same day, *Opportunity* returned breath-taking color images of its landing site, showing dark reddish-brown soil and rock outcroppings. The spacecraft had landed in a small impact crater, which JPL named Eagle Crater. The rover’s Pancam returned startling images of its amazing surroundings during the next several sols. *Opportunity* rolled off its lander in the

early morning hours of 31 January. By 6 February, the *Spirit* mission team had also succeeded in restoring the rover to health, having stopped the rover's constant system rebooting, cleared its flash file memory of thousands of files by reformatting, and uploaded critical software to restore full functionality. The same software was sent to *Opportunity* to prevent a similar occurrence. The two rovers were now ready for their missions of unknown duration. It was hoped that they would operate for their full 90-sol mission plan. JPL and the world would be pleasantly surprised.

Spirit explores Gusev Crater

Spirit resumed its mission in the first week of February and put the RAT to work grinding a portion of the rock Adirondack, which was examined by the microscopic imager on sol 34. Over the next twenty sols it would use its suite of instruments and cameras as it examined soils and rocks while driving in the direction of Bonneville Crater. On its trek toward the crater, *Spirit* took the first image of its home planet, Earth. After it reached Bonneville Crater on sol 66, scientists estimated that the shallow crater measured roughly 200 meters in diameter. From the rover's cameras and instruments, scientists discovered no identifiable layering in the walls of the crater, but *Spirit* spent several more sols moving along the rim of the crater in an



The MER rovers were fitted with a rock abrasion tool capable of a 5 cm-diameter cut. Close-up images were taken on 7 March 2004 by the microscopic imager and four frames were assembled to produce this final image. The specimen was a rock dubbed "Humphrey". (NASA/JPL)

effort to discover more intriguing surface features. As the rover passed sol 80, it looked like both *Spirit* and *Opportunity* would meet their mission length requirement and go into the extended portion of the mission that had been planned for. On 8 April 2004, NASA announced that it was extending the MER missions by an additional five months.

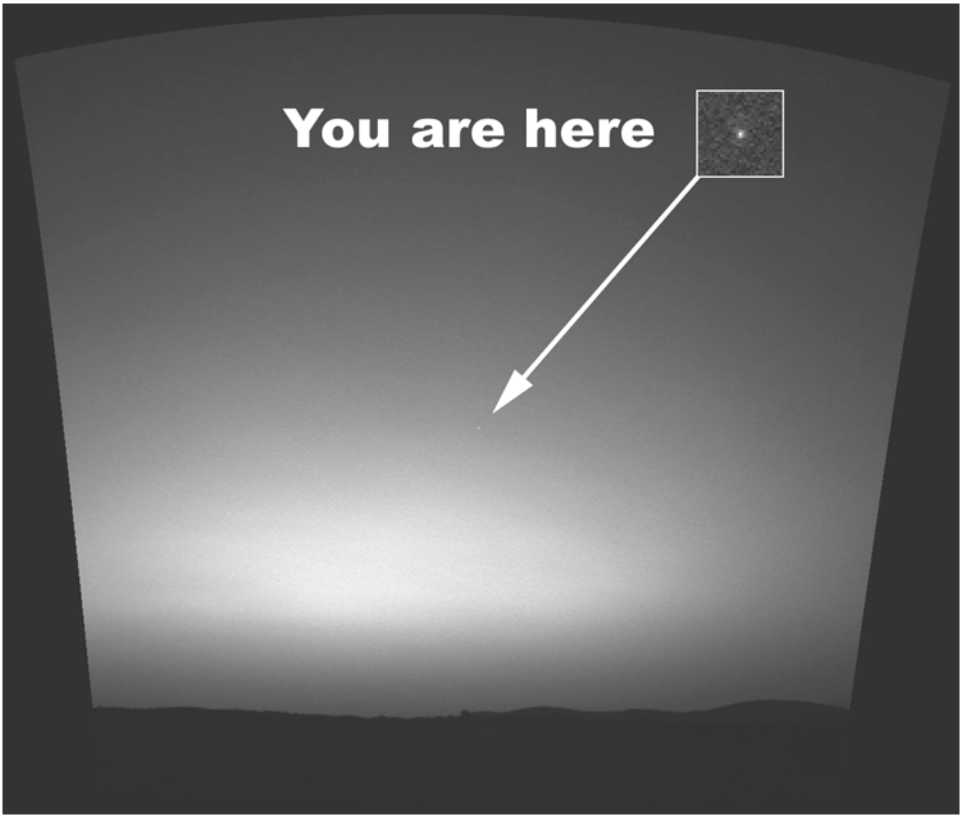
This would permit JPL to set *Spirit* off toward the Columbia Hills more than two kilometers away. The rover's rocker-bogie suspension system and individual wheel drives continued to perform perfectly, the solar panels were providing the needed electrical power as there was very little dust on them, and the scientific instruments continued to perform to specifications. *Spirit* helped scientists to ascertain sedimentary rocks that had evidence of water action upon them. The ground the rover had been traveling over in its quest for Columbia Hills was relatively flat but was strewn with rocks of all sizes over most of the surface. However, the rover was slowly approaching an area of the plain with fewer rocks. It would be slow going, but the rover had much exploring and scientific investigation to do before it would get there. *Spirit* was driven in virtually a straight line toward Columbia Hills and took two months to approach the base of the hills.

"This is the first time we've had a close look at hills on Mars," Dr. James Rice, one of the rover's science team members from Arizona State University, Tempe, said in a JPL news release. "We could only observe Twin Peaks from a distance and wonder about them," Dr. Rice stated of the hills visible from the Pathfinder lander, "but with a more capable rover we can get to Columbia Hills."

Spirit began its climb into Columbia Hills after more than 150 sols on the Martian surface. Scientists examining images from the rover saw one rock having unique formations and took the rover in for a closer look. Using the microscopic imager, they believed they were looking at a rock containing hematite – in many cases this is formed in the presence of water on Earth. They dubbed the rock Pot of Gold. However, *Spirit* had developed problems with its right front wheel and JPL chose to turn the rover around and essentially drive it backwards. This was another contingency JPL had considered and planned for. The engineers were impressed with the rover's durability, and this driving mode would allow the team to continue conducting science. Although it was mid-July, the Martian winter was approaching, but as it continued its slow climb and passed sol 200 (29 July), *Spirit* discovered rock outcrops that came under its examination. One rock in particular, named "Clovis" was examined by the rover's APXS, which found surprisingly high levels of bromine, chlorine and sulfur inside the rock.

"We have evidence that interaction with liquid water changed the composition of this rock," Dr. Steve Squyers of Cornell University said at the weekly MER mission update for the media. "This is different from the rocks out on the plain, where we saw coatings and veins apparently due to the effects of a small amount of water. Here, we have a more thorough, deeper alteration, suggesting much more water."

In September 2004, Mars entered into planetary conjunction. It passed behind the Sun and communication with *Spirit* and *Opportunity* was lost for twelve days. The rovers remained in place but continued to make observations. This was the most difficult time for the rovers in terms of power generation in the midst of the Martian



At the start of sol 63, Spirit took this image of its home planet more than 250 million kilometers away. This is the first image ever taken of Earth by a robotic probe on the surface of another planet beyond the Moon. (NASA/JPL/Cornell/Texas A&M)

winter. Communications resumed when Mars appeared from behind the Sun, and JPL gave the MER program another extension.

"Although *Spirit* and *Opportunity* are well past warranty, they are showing few signs of wearing out," Jim Erickson, JPL's rover program manager said at a news conference during the third week of September. "We really don't know how long they will keep working, whether days or months. We will do our best to continue getting the maximum possible benefit from these great national resources."

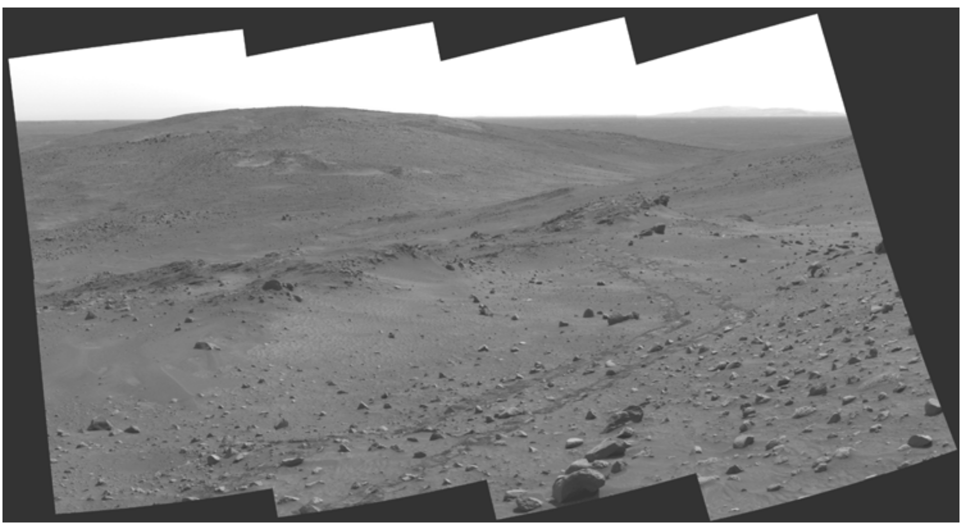
Spirit spent the next several months taking a cautious and winding route up the face of Columbia Hills, with the recalcitrant wheel slowing its progress. After weeks of diagnosing the problem at JPL, engineers succeeded in devising a work-around solution that restored the wheel's functionality. By 3 January 2005, *Spirit* had spent a full year on the planet, returning scientific data and startling images that continued to amaze and impress scientists. The rovers had succeeded in generating unprecedented interest around the world, with JPL's Martian Exploration Rover website having achieved more than nine billion "hits".

The rover *Spirit* was directed to begin its ascent of Husband Hill within the Columbia Hills. The hill was named after Rick Husband, who was Commander of the Space Shuttle *Columbia* that disintegrated upon re-entry on 1 February 2003. This part of the mission would mark a long phase of exploration, scientific discovery and return of many images. By the end of April, *Spirit* had climbed up half the elevation of Husband Hill and on 22 August 2005, the intrepid rover reached the summit, eighty-two meters above the plains of Gusev Crater. *Spirit* sent back a breathtaking panorama mosaic of its position on sol 582 (23 August), but this long climb to the top also had a definite purpose.

"This climb was motivated by science," said Steve Squyers at a news conference. "Every time Spirit has gained altitude, we've found different rock types. Also, we're doing what any field geologist would do in an area like this: climbing to a good vantage point for plotting a route."

"We're finding abundant evidence for alteration of rocks in a water environment," deputy principal investigator for the rovers' science instruments Ray Arvidson stated during the same news conference. "What we want to do is figure out which layers were on top of which other layers. To do that, it has been helpful to keep climbing for good views of how the layers are tilted to varying degrees. Understanding the sequence of layers is equivalent to having a deep drill core from drilling beneath the plains."

While on Husband Hill, *Spirit* made astronomical observations, taking images of the two moons Phobos and Deimos at night. The rover spent more than 100 sols performing detailed examinations of the varied rocks, outcroppings and soil, before



During its climb to the summit of "Columbia Hills", MER Spirit took this mosaic of images toward "Clark Hill" and the "Methuselah" Outcrop below, on sol 454 (13 April 2005). Engineers responsible for driving the rover had to drive a zigzag pattern to reach the top. (NASA/JPL/Cornell)

beginning its descent in mid-October with more than 630 sols under its wheels. On 20 November 2005, the Mars Exploration Rover team celebrated *Spirit's* first Martian year anniversary, equivalent to 687 Earth days. One of the benefits of its stay on Husband Hill was the wind gusts that kept the rover's solar panels relatively free of dust, allowing the rover to continue to receive its required amount of solar energy. As it was approaching the plain of Gusev Crater, it took images over a period of days at the end of December that made up a mosaic of the impressive sand dunes near a site identified as El Dorado. On 12 January 2006 (sol 721), *Spirit* stirred up the sandy soil with its wheels and revealed bright salts with iron-bearing sulfates, providing more evidence of liquid water having once been present.

The rover's next destination was Home Plate, a low plateau, to perform detailed studies of some of the uniquely-shaped rocks there. These rocks revealed many layers, with coarse granular structure at the bottom and finer structure at the top in a manner that indicated settled volcanic debris. The rover eventually left Home Plate and was directed toward McCool Hill, but on sol 779, *Spirit's* right front wheel seized completely. JPL calculated that the rover's wheels had performed more than thirteen million revolutions, traveling nearly seven kilometers. Mission planners moved the rover to a slope where its solar panels were better oriented toward the Sun in preparation for the long Martian winter. Here, *Spirit* would surpass sol 800.

Opportunity **explores Meridiani Planum**

Opportunity had made many wondrous discoveries of its own and returned images revealing the ancient history of Mars that would keep scientists poring over them for years. JPL spent a week preparing the rover, checking all its instruments, and raising it up from its stowed position before it rolled onto the surface of Eagle Crater on 31 January 2004. There was much for the rover to investigate within the crater. A photographic pan of the landing area revealed layered bedrock outcrops less than ten meters away, which project scientists identified as "rocks in place." These were rocks that had remained in the same place where they had originally formed. Such rocks hold a wealth of planetary history, and even from a distance, scientists studying the images could identify sedimentary layers, giving strong indications of the presence of water eons ago. Close inspection of the soil on the crater's floor with the microscopic imager revealed small spheres of hematite, a scientific fingerprint indicating that water had been present.

Opportunity spent weeks performing detailed examinations of the entire outcrop within Eagle Crater, stopping at particular rocks for study. Findings conclusively proved that water had at one time been present. This was a prime mission objective of the Mars Exploration Rovers.

"Liquid water once flowed through these rocks," said Dr. Steve Squyers at a press conference in March. "It changed their texture, and it changed their chemistry. We've been able to read the tell-tale clues the water left behind, giving us confidence in that conclusion. We think *Opportunity* is parked on what was once the shoreline of a salty sea on Mars."

After spending more than two fruitful months exploring and revealing discoveries within Eagle Cater, *Opportunity* rolled up and out of the shallow crater on sol 57 and

headed for a much larger crater over 700 meters away. This crater would be identified as Endurance Crater and would prove to be an even more spectacular find. The walls of Endurance Crater proved to be quite steep, and considerable discussion went on at JPL as to whether the rover should even attempt to enter it.

"This is a crucial and careful decision for the Mars Exploration Rovers' extended mission," said Dr. Edward Weiler, NASA's Associate Administrator for Space Science. "Layered rock exposures inside Endurance Crater may add significantly to the story of a watery past environment that *Opportunity* has already begun telling us. The analysis just completed by the rover team shows the likelihood that *Opportunity* will be able to drive to a diagnostic rock exposure, examine it, and then drive out of the crater. However, there's no guarantee of getting out again, so we also considered what science opportunities outside the crater would be forfeited if the rover spends its remaining operational life inside the crater."

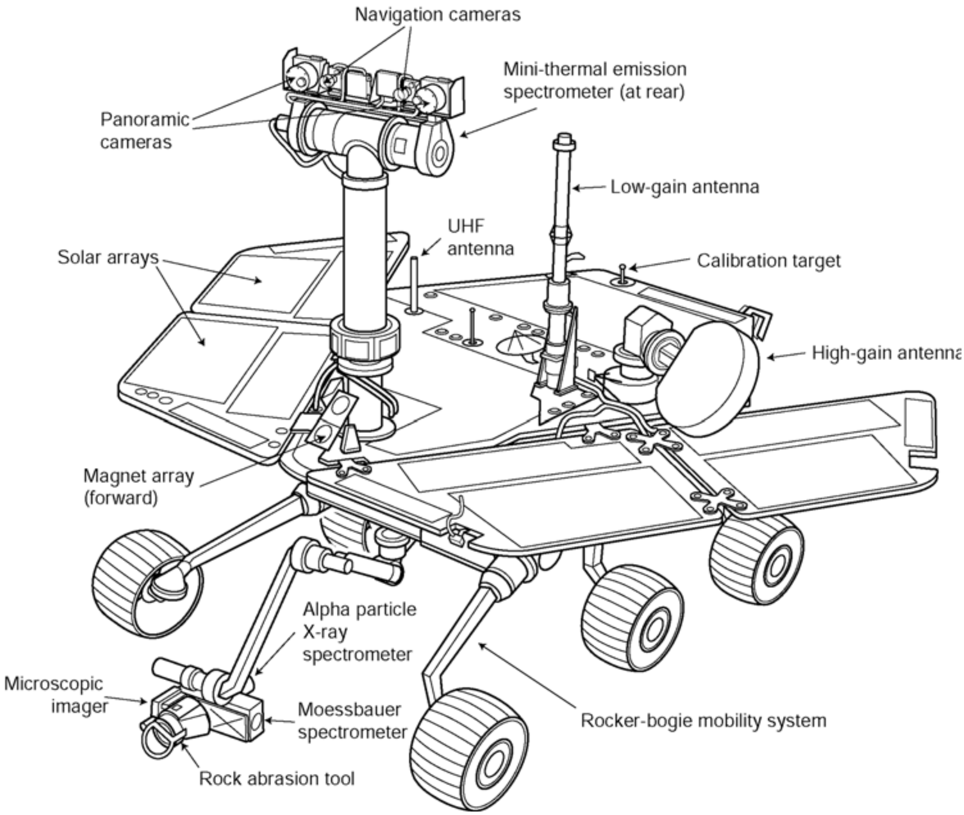
JPL methodically mapped the rover's entry route, its path of exploration within the crater and possible exit strategies. What the mission team did not know was that it would spend the next six months within Endurance Crater, exploring literally the history of Mars with *Opportunity*. The images the rover took within Endurance became some of the most amazing and revealing of its mission, and NASA proudly displayed the assembled mosaics as wide-angle panoramas. The rover brought all its instruments to bear upon the varied rock walls of the crater and found more evidence of water having once been present. It found significant levels of chlorine, which increased as it drove deeper into the crater, while concentrations of magnesium and sulfur decreased. During the Martian winter, the pace of *Opportunity's* exploration slowed in order to conserve and store precious solar energy.

Prior to leaving the crater, *Opportunity* spent considerable time inspecting exposed rock layers along the upper part of the crater wall, called Burns Cliff.

"In the lower portion of the cliff," Dr. Squyers stated in mid-December 2004, "the layers show very strong indications that they were last transported by wind, not by water like some layers higher up. The combination suggests that this was not a deep-water environment but more of a salt flat, alternately wet and dry."

Opportunity successfully climbed up and out of Endurance Crater on sol 315 in December. The rover was then sent to make a thorough inspection of its battered heat shield, which had landed near Endurance, before heading off on a route directly south toward its next exploration target, Vostok Crater, more than a kilometer away. "Little did we know a year ago that we'd be celebrating a year of roving on Mars," Dr. Charles Elachi, director of the Jet Propulsion Laboratory, stated in January 2005. "The success of both rovers is tribute to the hundreds of talented men and women who have put their knowledge and labor into this team effort."

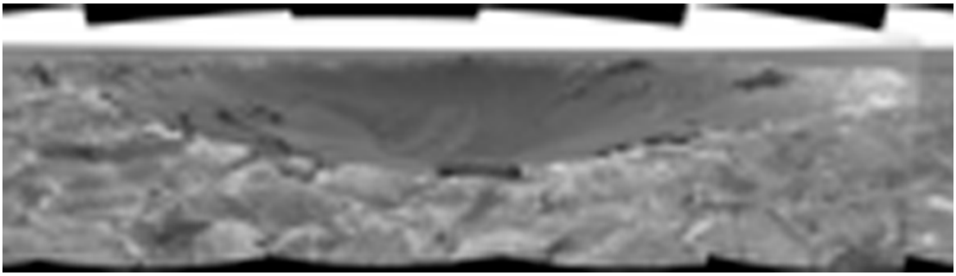
Not far from the heat shield, the rover made a startling discovery: an iron meteorite. Its origin and composition was confirmed by the Mossbauer and the APXS instruments. "I never thought we would get to use our instruments on a rock from someplace other than Mars," Dr. Squyers said during the news conference that January. "Think about where an iron meteorite comes from: a destroyed planet or planetesimal that was big enough to differentiate into a metallic core and a rocky mantle."



This illustration shows key components of the MER rover from the top but does not show the bulk of the electronic equipment inside the body of the rover. (NASA/JPL)

The plain *Opportunity* traveled over was surprisingly smooth, unlike the rugged surface *Spirit* had to contend with, so its progress was relatively swift. Then, at the end of April on sol 446, the rover got bogged down in sand dunes. In one of JPL's laboratories, engineers formulated a Martian soil simulant and ran tests with a rover test vehicle with identical wheels to experiment with different methods of extracting *Opportunity* from its situation. The solution to incrementally move the rover without sinking further into the dunes took weeks to develop, test, and employ with the actual vehicle on Mars. Finally, after more than four weeks of effort, the JPL team succeed in getting the rover free of the dunes.

"After a nerve-wracking month of hard work, the rover team is both elated and relieved to finally see our wheels sitting on top of the sand instead of half buried in it," said Jeffrey Biesiadecki, a JPL rover mobility engineer. JPL decided to drive the rover more cautiously now, considering its surface conditions, and it took more than 100 sols before *Opportunity* arrived at Erebus Crater. This was the largest crater the rover had encountered so far, at 300 meters in diameter, and would prove to be



MER Opportunity took a panorama of images of Endurance Crater on sol 115 and 116 (21 and 22 May 2004). JPL used these images to plot Opportunity's entry into the crater and its path once inside. (NASA/JPL)

another rich exploration site. Exposed bedrock displayed cracks and fissures, indicating that the crater had repeatedly experienced wet and dry conditions over a long period of time.

On 26 November 2005 (sol 654), the robotic arm on the rover failed to function properly. After operating on the surface of Mars for the equivalent of nearly two Earth years, both rovers were starting to wear out. JPL engineers worked to determine the problem with the rover's robotic arm and *Opportunity* was parked on a rock outcrop called Olympia, with dark sandy dunes all around it, while a solution was sought to return the robotic arm back to service. The rover panoramic camera was put into service, thoroughly imaging the entire area and making yet another discovery. It found what JPL scientists called "festooned cross bedding" formed by flowing liquid water. After weeks of conducting tests on a similar robotic arm at JPL, they were able to get *Opportunity's* robotic arm partially extended, and it would be used in this position from now on. It used the microscopic imager on 27 January 2006 (sol 715) to get close-ups of the rocks displaying "festooned cross bedding."

The rover continued to explore Erebus Crater for the month of February and part of March, employing its microscopic imager on the crippled robotic arm and continuing to return superb images from the PanCam. Studying images taken by the *Mars Orbital Surveyor* camera, JPL decided to send *Opportunity* further south toward Victoria Crater two kilometers away. On sol 760, it began its trek to this crater, which measures approximately 750 meters in diameter. Both *Spirit* and *Opportunity* continued to amaze JPL's engineers, scientists and managers in their exploration of Mars.

"I don't think that any of us really seriously considered that the rovers would last this long," Andrew Mishkin admitted. "They could continue for a while longer or we could have a failure any day. One of the rovers one day may just not wake up or be able to communicate with us any more."

The Jet Propulsion Laboratory knows that day for each rover will arrive, but the amount of scientific data and number of images they have sent back to Earth will keep scientists busy for years, a legacy that will continue long after the rovers themselves have ceased operating.

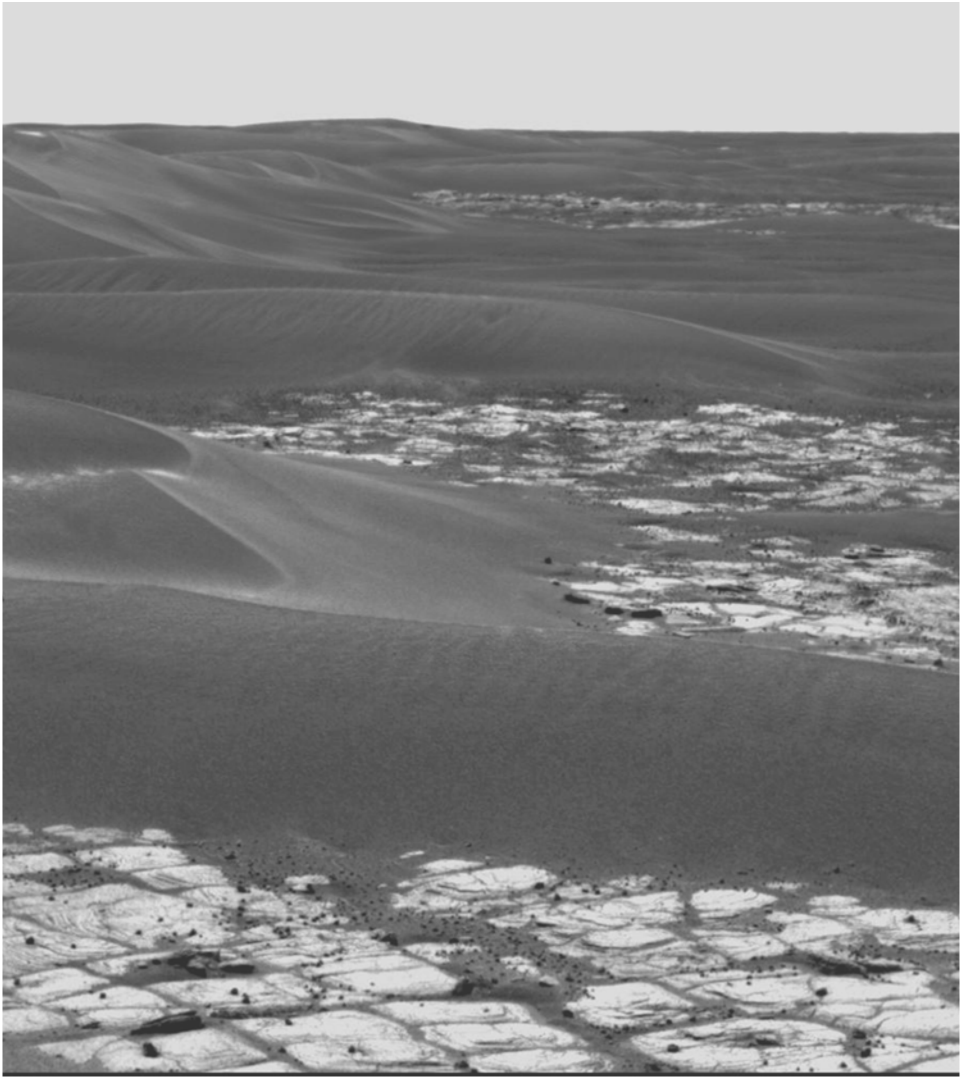
MARS SCIENCE LABORATORY

In October 2000, NASA unveiled its ambitious Mars Exploration Program for the next two decades. It included orbiters, landers, rovers and even a sample return mission. Among the six major exploration programs was a mobile scientific laboratory. This rover would be even larger than the Mars Exploration Rovers with even more scientific capability. In its press release on 26 October, 2000, the agency stated, "NASA proposes to develop and to launch a long-range, long-duration mobile science laboratory that will be a major leap forward in surface measurements and will pave the way for a future sample return mission. NASA is studying options to launch this mobile science laboratory mission as early as 2007. This capability will also demonstrate the technology for accurate landing and hazard avoidance in order to reach what may be very promising but difficult-to-reach scientific sites."

The formal name of this spacecraft became the Mars Science Laboratory. Everything about the MSL would be big: the rover, its scientific return and its projected budget of more than 850 million dollars. This was never intended to be a Discovery mission, but instead, the program was conceived to see what could be accomplished in Mars surface exploration when budget and schedule were not so constrained. With up to ten times the scientific instrument payload of the MER rovers, a mission length of at least one Martian year (equivalent to two Earth years) and the capability of operating for years without the need for solar power, the potential landing sites for the MSL will encompass much of the planet's surface. Its primary mission is to study the past and present habitability of the planet Mars. In other words, it will search for evidence of past life and possible evidence of present microbial life, and determine whether future crewed missions to Mars can remain on the planet for extended periods and extract the essential elements for living on the Martian surface.

While the Mars Exploration Rovers were the focus of attention around the world during 2003 and 2004, the managers, engineers and scientists at NASA Headquarters and at the Jet Propulsion Laboratory were quietly working on the scientific scope, initial design and mission planning of MSL, now scheduled for launch in 2009. In April 2004, NASA issued an Announcement of Opportunity for proposals to provide the payload instruments and scientific investigations they would perform on the MSL. In December 2004, NASA selected eight of the proposals and announced their principal investigators:

- Mars Science Laboratory Mast Camera; Michael Malin, Malin Space Science Systems, San Diego, California.
- ChemCam: Laser Induced Remote Sensing for Chemistry and Micro-Imaging; Roger Weins, Los Alamos National Laboratory, Los Alamos, New Mexico.
- MAHLI: Mars Hand Lens Imager for the Mars Science Laboratory; Kenneth Edgett, Malin Space Science Systems, San Diego, California.
- The Alpha-Particle X-ray Spectrometer for Mars Science Laboratory; Ralf Gellert, Max-Planck Institute for Chemistry, Mainz, Germany.



From the rim of "Erebus Crater," Opportunity took this image on sol 608 (9 October 2005). Martian soil has drifted over portions of rock outcrop within the crater. (NASA/JPL-Caltech/Cornell)

- CheMin: An X-ray Diffraction/X-ray Fluorescence instrument for definitive mineralogical analysis in the Analytical Laboratory of Mars Science Laboratory; David Blake, NASA's Ames Research Center, Moffett Field, California.
- Radiation Assessment Detector; Donald Hassler, Southwest Research Institute, Boulder, Colorado.

- Mars Descent Imager; Michael Malin, Malin Space Science Systems, San Diego, California.
- Sample Analysis at Mars with an integrated suite consisting of a gas chromatograph mass spectrometer, and a tunable laser spectrometer; Paul Mahaffy, NASA's Goddard Space Flight Center; Greenbelt, Maryland.

The MSL would also have instruments provided by the Russian Federal Space Agency and the Spanish Ministry of Education and Science. The next phase of these proposals would be preliminary design studies to integrate the scientific instruments on the MSL platform and to establish the development, test and delivery schedule of the instrument payloads in keeping with the MSL program schedule.

"MSL is the next logical step beyond the twin *Spirit* and *Opportunity* rovers," said Dr. Ghassern Asrar, NASA's Deputy Associate Administrator for the Science Mission Directorate, when announcing the winning proposals. "It will use a unique set of analytical tools to study the Red Planet for over a year and unveil the past and present conditions for habitability of Mars."

The Mars Science Laboratory Mast Camera (MastCam)

With each new Martian rover, the image quality has made dramatic improvements, and that was the goal for the MSL. Like the MastCam on the MER rovers, the MSL MastCam will take color and three-dimensional stereo images, but it will also take high-definition color video on Mars at ten frames per second and it will have a 10:1 zoom lens that can be used for both single image and video. It will also be able to take multi-spectral monochromatic images using filters that will reveal key elements in the soil and rock. The MastCam will process images separately from the MSL's own CPU and will have an internal data buffer that will permit storage of thousands of individual images or several hours of high-definition video for transmission to Earth.

Laser-Induced Remote Sensing for Chemistry and Micro-Imaging (ChemCam)

MSL will employ a laser fired from the rover's mast assembly that will then analyze the composition of the vaporized rock or soil from the resulting plasma of ionized material using the on-board spectrograph. The laser will also be used to clear dust from rocks and will use its remote camera to obtain highly detailed images of areas up to ten times smaller than those capable of being observed by the MER rovers. The ChemCam will be able to remotely analyze distant rocks or other geologic forms from one to nine meters away, where the MSL is unable to approach, and will be able to identify the composition of soils and small stones and determine whether they are volcanic or sedimentary. It will also be able to measure a great many chemical elements within the rock or sold specimens, including trace elements having less than 1,000 parts per million. Most importantly, it will be able to recognize ice and even water molecules in minerals. Like the mast assembly on the MER rovers, the MSL mast assembly will be able to rotate 180 degrees in both directions and will have elevation pan capability.

Mars Hand Lens Imager (MAHLI)

In its basic form, the hand lens (usually worn hanging from the individual's neck) has been an essential tool of geologists for many years. It allows close-up magnification of the rock being studied to determine its elemental structure and probable means of formation. On the MSL, the MAHLI will provide the scientific teams on Earth with the ability to get extreme close-up views and images of rocks, soil and even dust. The camera lens, measuring four centimeters in diameter, will be self-focusing, and the camera will be capable of taking images of formations as small as 12.5 microns. The MAHLI will be able to examine objects using both white light and ultraviolet light, to better determine whether water has contributed to the specific areas being explored.

Alpha Particle X-Ray Specrometer (APXS)

The APXS used on the MSL will be even more capable than the instrument used on the MER rovers. The new APXS will have the ability to comprehensively examine soils and rocks. It's function is best described by JPL: "The APXS would be placed in contact with rock and solid samples on Mars and would expose the material to alpha particles and X-rays emitted during the radioactive decay of the element curium. X-rays are a type of electromagnetic radiation, like light and microwaves. Alpha particles are helium nuclei, consisting of two protons and two neutrons. When X-rays and alpha particles collide with atoms in the surface material, they knock electrons out of their orbits, producing an energy release by emitting X-rays that can be measured with detectors. The X-ray energies enable scientists to identify all-important rock-forming elements heavier than sodium."

Unlike the APXS used on the MER rovers, this new generation instrument would be able to operate during both the Martian day and night. While ten minutes would be sufficient to obtain information on the major elements from the soil sample or rock being examined, most APXS measurements will require two to three hours to reveal all the elements. This APXS is a project that involves a number of participants, including the Canadian Space Agency; the University of Guelph in Ontario, Canada; MDA Space Missions in British Columbia, Canada; the University of California in San Diego, California; and Cornell University in Ithaca, New York.

Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence Instrument (CheMin)

The primary function of the CheMin will be to study mineral composition formed by the action of liquid water and how other mineral substances were formed in the absence of water. Some of the minerals already found on previous Mars missions include magnetite, gypsum goethite, pyroxenes, olivine, jarosite and hematite. The CheMin will be looking for many other minerals and how they may have been formed by the movement of water. The MER rover *Opportunity* discovered erosion in solid rock in the walls of Endurance Crater, believed to be the result of flowing water. The MSL will collect small stones or pebbles and deposit them in a rock crusher which will grind them to almost a powder. A sieve will ensure that the

smallest grains are placed on a sample holder, which will vibrate to mix the sample. CheMin will then pass X-rays through the sample to produce X-ray diffraction which will be absorbed by a detector. This will identify the specific minerals in the sample because each mineral has a distinct diffraction pattern. A charge-coupled device (CCD) will collect diffraction and fluorescence given off during the X-ray operation.

Radiation Assessment Detector (RAD)

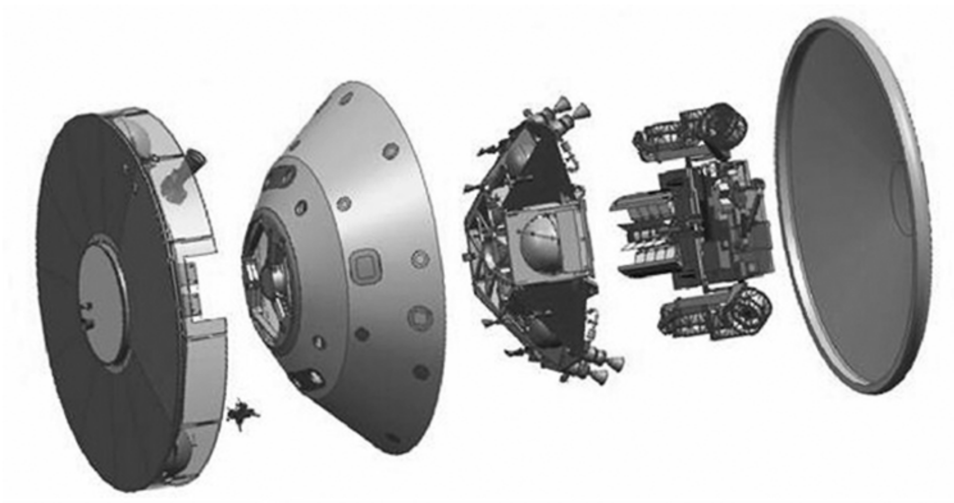
A primary function of the MSL is to determine the habitability of Mars for future crews. The purpose of the RAD is to measure the levels of radiation coming from space to the Martian surface and to measure radiation emitted from the surface soil and rocks. The RAD will be able to measure protons, ions of certain elements, gamma rays and neutrons, measured by a series of thin silicon detectors. The data collected from this instrument will allow scientists to measure the radiation dose both instantaneously and over a period of time to determine if it is within the limits humans can absorb without physical consequences. A key concern in long-term space exploration is the exposure to radiation. The RAD is one of the lightest-weight instruments and will have one of the lowest power consumption levels on the MSL.

Mars Descent Imager (MARDI)

Although classified as an instrument, the MARDI will perform a different kind of analysis for different purposes than the other instruments aboard the MSL. A first-generation Mars Descent Imager was employed during the landing phase of EDL for the MER rovers. It was designed to determine horizontal velocity and send the information to the TIRS system so that the airbag-protected lander and rover could drop straight to the planet's surface. The second generation MARDI is much more sophisticated and has the benefit of more development time. It will take color video of the landing site at five frames per second during the MSL's parachute descent. This will provide vital information on the spacecraft's precise landing location as it descends to the surface, and will provide a terrain map of the area to help science planners establish the MSL's paths of exploration. It will also allow the spacecraft to make corrections to avoid large boulders, cliffs or other surface features as the MSL touches down on the planet's surface. (See MSL EDL below).

Sample Analysis at Mars (SAM)

The largest and heaviest instrument aboard the MSL is the Sample Analysis at Mars, weighing thirty-eight kilograms. SAM is, in itself, a suite of instruments. Engineered by the Goddard Space Flight Center, it contains three instruments that include a mass spectrometer, a tunable laser spectrometer and a gas chromatograph. The mass spectrometer will separate compounds and elements by their mass and perform measurements and identification. The laser spectrometer will be capable of measuring isotopes of oxygen, hydrogen, nitrogen and carbon in the Martian atmosphere (which contains predominantly carbon dioxide) and will detect any water vapor, methane, hydrogen peroxide and nitrous oxides present with a sensitivity of ten parts per thousand. The gas spectrometer will take samples of soil



The spacecraft for the Mars Science Laboratory includes the cruise stage, backshell, descent stage with skycrane, MSL rover, and heat shield. (NASA/JPL)

or rock and heat them until they vaporize. The gases given off during this process will be separated and analyzed. The SAM will essentially look for the ''stuff of life'' in Mars' distant past and perhaps find evidence of the presence of microbial life.

In addition to this suite of scientific instruments on the MSL, there are two additional instruments. The Dynamic of Albedo Neutrons (DAN) instrument will be used to detect subsurface water or ice. Frozen or liquid water absorbs and slows neutrons escaping from the planet's surface as a result of cosmic ray activity more than other substance. These slower neutrons will be measured by the DAN in an effort to find this key element of biological life. It will be sensitive enough to detect water ice content as small as one-tenth of one per cent. Scientists estimate that water ice may constitute from thirty to fifty per cent of the subsurface deposits near the Martian's poles. The Rover Environmental Monitoring Station (REMS) will act as the MSL's weather station, monitoring wind speed and direction, atmospheric pressure, humidity, temperature and ultraviolet radiation from the Sun. This instrument will be mounted on the MSL's mast assembly. The Centro de Astrobiologia in Spain will provide this instrument.

THE MSL ROVER CONFIGURATION

The Mars Science Laboratory – the ultimate planetary rover – will be a much larger and heavier rover than the MER rovers. It will have a wheelbase of 1.5 meters, an equipment deck height of 1.1 meters with a surface clearance of roughly 0.6 meters, and an overall height to the top of the ChemCam on the Mast Assembly of 2.1 meters. JPL estimates the weight of the MSL at 775 kilograms. It will employ a

bigger and even more effective rocker-bogie suspension design, with forty-centimeter-diameter wheels capable of rolling over seventy-five-centimeter-high obstacles. Due to mission duration, potential landing site location and power requirements, JPL will employ the newest generation Radioisotope Thermoelectric Generator (RTG), which is a proven technology first employed on the successful Viking 1 and Viking 2 landers and on the Apollo Lunar Surface Experiment Packages (ALSEP) deployed on the Moon. The RTG is capable of providing power for the MSL for years. Drawing from lessons learned from the MER rover software experiences, the MSL flight software will employ Mission Data Systems (MDS)-based architecture and JPL's systems engineering methodology that will be much more stable, robust and readily upgradeable. The MSL's computer, CPU and memory will be the most advanced ever employed in order to handle all the rover's operations, scientific functions and communications. It will employ high-gain, low-gain and UHF antennas. The MSL will have a more sophisticated robotic arm that will be fully articulated to place samples within the sample analysis instruments. The MSL will undergo its first field tests during 2008.

Launch vehicle and spacecraft

The size and weight of the MSL and its spacecraft will require a more powerful launch vehicle than the Boeing Delta II used for the previous Mars rover missions. The entire MSL spacecraft payload is expected to be 2,800 kilograms with a heat shield/spacecraft diameter of 4.5 meters. The Viking 1 and 2 landers and their orbiters were launched aboard Titan/Centaur rockets with solid rocket motor boosters. The Titan IV rocket was retired in 2005 so available alternatives have been studied. The Titan IV was replaced by Boeing's new Delta IV and Delta IV Heavy, and the Lockheed Martin Atlas V with Centaur upper stage is also a possible launch vehicle. The Delta IV family of launch vehicles is very versatile. The Delta IV Medium + with Delta III upper stage, five-meter-diameter payload fairing and two strap-on Alliant 1.5-meter solid rocket graphite epoxy motors is capable of boosting 4,640 kilograms to geosynchronous transfer orbit (GTO) and on to Mars. The Atlas V family of launch vehicles is equally varied. The Atlas V (version 501) with five-meter fairing and no additional boosters is capable of launching a 3,971 kilogram payload to GTO. Both Delta IV and Atlas V are capable and reliable launch vehicles, and NASA's decision on which to use may have simply been based on costs for the launch vehicle and launch support. NASA considered both of these launch vehicles carefully before selecting Lockheed Martin Commercial Launch Services, Inc. in June 2006. They will deliver an Atlas V to launch the MSL from Launch Complex 41 at Cape Canaveral Air Force Station in Florida.

The MSL spacecraft that will go atop the Atlas rocket will have a similar configuration as that for the Mars Exploration Rover mission. It will include the cruise stage, the aeroshell with backshell and heat shield and, within the aeroshell, the parachute system, powered descent stage with Sky Crane, and the MSL rover. The cruise stage will make several trajectory corrections and will separate from the aeroshell prior to entering the Martian atmosphere. After atmospheric entry and maximum deceleration, the parachute will deploy, slowing the spacecraft further.

Three generations of Mars rover wheels are shown here. From left, Pathfinder *Sojourner*, Mars Exploration Rover and the Mars Science Laboratory. (NASA/JPL)

The heat shield will be jettisoned and start of the MARDI phase of descent and once powered descent is initiated, the backshell and parachute will separate from the Sky Crane. The MSL, with its suspension and wheels fully deployed, will be slowly lowered from the Sky Crane to the Martian surface by cables as the powered descent stage hovers in position. Once the MSL is on the planet's surface, the cables will be severed and the descent stage with Sky Crane will fly away and crash land a safe distance from the MSL.

Once on the surface, the MSL will go through a complete system checkout phase and verification of system health with JPL. Landing in 2010, the MSL will begin a new decade of Martian exploration with countless new discoveries to be made.

Landing site selection

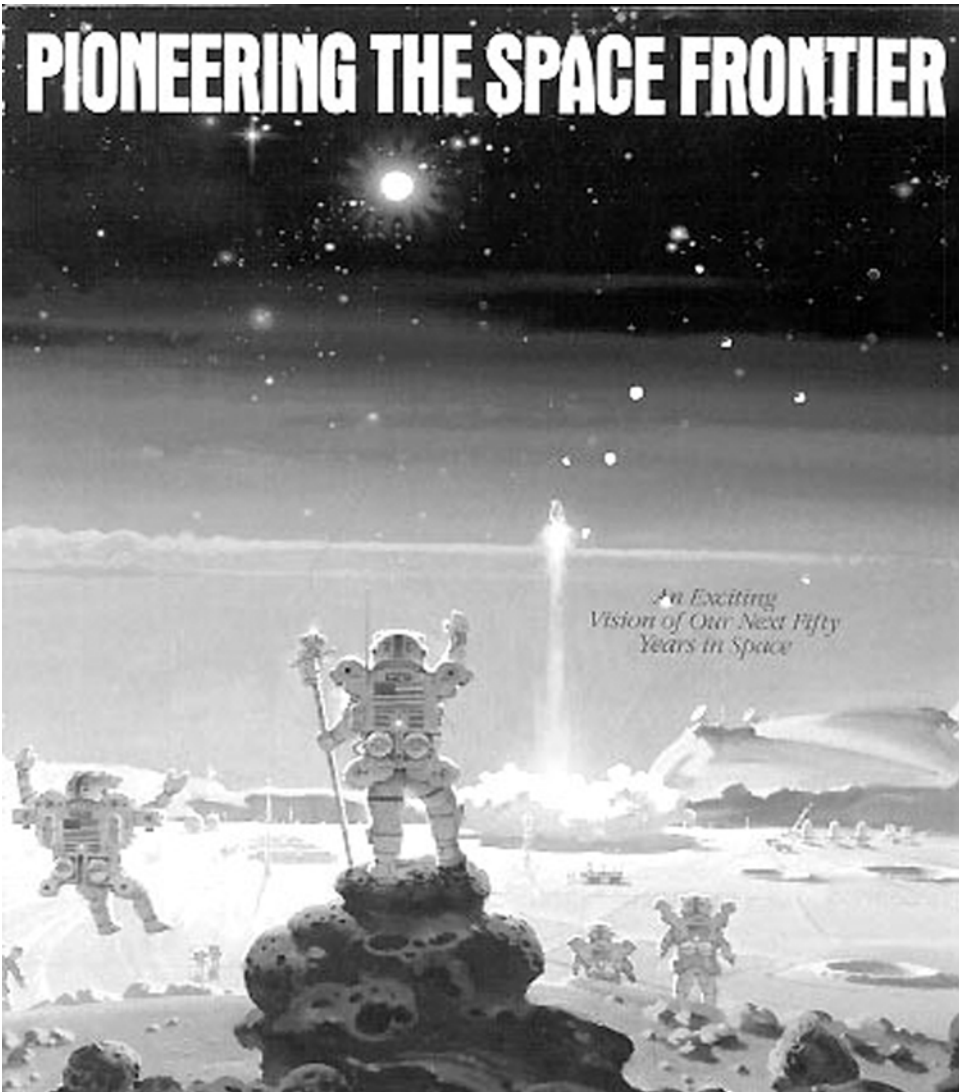
Due to the capabilities of the Mars Science Laboratory and its means of power, it will not be limited to a narrow equatorial band on Mars. Vast regions of Mars are now open for exploration, up to plus and minus sixty degrees of latitude, and this makes the task of MSL landing site selection both exciting and difficult. Early in 2006, NASA issued a Call for Abstracts for the First Landing Site Workshop for the 2009 NASA Mars Science Laboratory Mission, which was held in Pasadena, California in June 2006. NASA's Mars Site Steering Committee, co-chaired by Matt Golombek of JPL and John Grant of the Smithsonian Institution, would use the abstracts presented to begin the scientific debate in narrowing the choices first to

thirty, then to ten potential landing sites, ready for the eventual selection of the most desirable single site which will be determined in 2009. Among the candidates for landing sites presented at the workshop were Gale Crater, Argyre Planitia, Holden Crater, Eberswalde Crater, Terby Crater, various sites within the massive Valles Marineris, Meridiani Planum, and other proposed sites. With over 120 principal investigators, co-investigators and collaborators involved in the MSL program, NASA plans to hold the site selection workshops annually until 2009 when the final chosen site will be picked. Orbital assets such as NASA's *Mars Reconnaissance Orbiter* and ESA's *Mars Express* will be used by the Mars Site Steering Committee to narrow the field of potential proposed sites. Factors influencing site selection include the operational mission of the MSL, latitude, altitude from minus two kilometers to no greater than two kilometers (with the lower altitudes preferable), a landing ellipse within ten kilometers with a surface slope of fifteen degrees or less within a five meter length, scaled to ensure rover landing stability and mobility, rock size and ruggedness of the landing area, prevailing and surface winds, and other factors. The scientific data returned from *Sojourner* and Mars Exploration Rovers *Spirit* and *Opportunity* will contribute to the decision-making process for the MSL landing site.

THE EXPLORATION OF SPACE AND LIFE ON EARTH

The United States space exploration program and those of other nations have not only expanded our knowledge of the solar system and the universe, they have greatly enhanced the lives of many people on Earth. The technological benefits to society as a result of the exploration of Mars in particular and space exploration in general have provided untold benefits to countless millions for decades. There is, however, yet another benefit that influences a new generation of space enthusiasts.

"My personal view on the greatest impact of the Mars program is in the way it can inspire people," said Andrew Mishkin. "When we are doing missions that are going to other planets and exploring, it is one of the few things we invest in that is actually using our potential in a positive way and showing results that we can give back to everybody. Having the Mars program in the age of the Internet where people can actually go and pull down the photos almost instantly after they have come down to Earth I just think is a major opportunity for us to inspire kids and excite people about things that can be done in science and engineering. I think that has a strong ripple effect throughout society and contributes to us having engineers and scientists in many fields."



President Ronald Reagan established the National Commission on Space in 1984. The Commission published its findings in *Pioneering the Space Frontier* in January 1986. The Shuttle *Challenger* disaster overshadowed this report's release and its visionary goals for America's future in space. (NASA)

The Vision for Space Exploration

The Lunar Roving Vehicle used on Apollo 15, 16 and 17 proved how valuable a rover could be to expanding the scope of the lunar mission and increased the level of scientific discovery this made possible. The Martian rovers *Sojourner*, *Spirit* and *Opportunity* proved that exploration of distant planets by robotic rovers could be of immense benefit, discovering the former presence of liquid water and how that presence influenced the formation of Mars' surface features. The Mars Science Laboratory holds the promise of discovering possible microbial life. Rovers, both robotic and human-driven, have proven their worth in the exploration of the Moon and Mars.

In the decades that followed Project Apollo, there were numerous proposals issued by NASA and space exploration advocacy groups for a return to manned space exploration on the Moon and even on to Mars. But Apollo was a hard act to follow. It was born of a geopolitical imperative that marshaled the United States like nothing seen since the Manhattan Project. Some argue that the International Space Station has been more technologically challenging than Apollo was, but many would disagree with that premise. Project Apollo broke more technological ground than anything undertaken by man in modern history. It literally transformed the industrial landscape of America, and it entailed an unprecedented degree of danger for the crews involved. The ISS, despite being a technological triumph, has never had the glamour, if you will, of Apollo. Nevertheless, human space exploration today is no less dangerous than it was decades ago. Certainly, United States astronauts are trained just as rigorously as ever.

What is certain is this: decisions by the U.S. government to commit to large engineering programs like the Space Transportation System and the International Space Station locked the nation into a mode of low-Earth-orbit activities that has precluded any human capability to return to the Moon or explore the most intriguing of the near planets: Mars. Nevertheless, efforts were made by the White House and NASA during the 1980s and 1990s to put forth ambitious human space exploration plans for purposes other than geopolitical supremacy. It is important to look at these proposals, why they failed to become policy and programs, and how the current Vision for Space Exploration (VSE) finally succeeded in becoming

national space policy and a funded NASA program, as part of its overall space exploration program. Rovers were understood to be a part of those early proposals, if not explicitly detailed in them. Similarly, human-driven rovers were not detailed in the early phases of the VSE program, but evolved with the formal mission profile of lunar surface operations.

POST-APOLLO PROPOSALS FOR AMERICA'S FUTURE IN SPACE

After the cooperative flight of Apollo-Soyuz in July 1975, no American astronaut flew into space until 12 April 1981, when John Young and Robert Crippen took *Columbia* into orbit on the maiden flight of the Space Shuttle, mission STS-1. America had entered a new era – the Shuttle Era – and it did not include manned exploration beyond low-Earth orbit. On 12 October 1984, President Ronald Reagan issued Executive Order 12490 establishing the National Commission on Space (NCS), in an attempt to focus America's future direction in space exploration. Specifically, it stated: "Pursuant to Section 204 of the Act, the Commission shall study existing and proposed United States space activities; formulate an agenda for the United States civilian space program; and identify long-range goals, opportunities, and policy options for civilian space activity for the next twenty years." On 29 March 1985, the president announced the members of the commission and appointed NASA Administrator Thomas O. Paine as its chairman. Among the Commission members were Apollo 11 astronaut Neil Armstrong and Shuttle astronaut Kathryn D. Sullivan. The Commission would issue a report on its findings and recommendations within twelve months.

Pioneering the Space Frontier

However, on 28 January 1986, the Space Shuttle *Challenger* disintegrated less than eighty seconds after launch, killing all seven crew members. The disaster stunned America and brought the U.S. human space flight program to a grinding halt. When the Commission report, *Pioneering the Space Frontier,* was issued several months later, it was overshadowed by the ongoing Rogers Commission investigating the *Challenger* accident. This national tragedy called into question America's space exploration capability, while many had forgotten or simply overlooked the fact that human space exploration could never be accomplished without risk.

Pioneering the Space Frontier, subtitled "An Exciting Vision of our Next Fifty Years in Space," made this call: "To lead the exploration and development of the space frontier, advancing science, technology, and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars." The report specifically cited twelve necessary milestones to implement this new vision:

- Initial operation of a permanent Space Station
- Initial operation of dramatically lower-cost transport vehicles to and from low-Earth orbit for cargo and passengers

- Addition of modular transfer vehicles capable of moving cargoes and people from low-Earth orbit to any destination in the inner Solar System
- A spaceport in low-Earth orbit
- Operation of an initial lunar outpost and pilot production of rocket propellant
- Initial operation of a nuclear electric vehicle for high-energy missions to the outer planets
- First shipment of shielding mass from the Moon
- Deployment of a Spaceport in lunar orbit to support expanding human operations on the Moon
- Initial operation of an Earth-Mars transportation system for robotic precursor missions to Mars
- First flight of a cycling spaceship to open continuing passenger transport between Earth orbit and Mars orbit
- Human exploration and prospecting from astronaut outposts on Phobos and Deimos
- Start-up of the first Martian resource development base to provide oxygen, water, food, construction materials, and rocket propellants

The benefits to mankind in general, and to the United States in particular, would be primarily threefold:

- By "pulling-through" advances in science and technology of critical importance to the Nation's future economic strength and national security
- By providing direct economic returns from new space-based enterprises that capitalize upon broad, low-cost access to space
- By opening new worlds on the space frontier, with vast resources that can free humanity's aspirations from the limitations of our small planet of birth

Pioneering the Space Frontier was as comprehensive as it was ambitious. The timing of its release and publication in the aftermath of the unforeseen Shuttle disaster, however, could not have been worse. NASA's focus was now on determining how the Shuttle disaster had occurred and how the Space Transportation System could be returned to flight. Congressional hearings were held from February to May 1986. The Rogers Commission, which included astronaut Dr. Sally K. Ride among the commission members, issued its report on 6 June 1986.

Leadership and America's Future in Space

Ride had become NASA's first woman astronaut flying, ironically, aboard the orbiter *Challenger* for STS-7 launched in June 1983. After the release of the Rogers Commission report, Ride was assigned to NASA Headquarters as Special Assistant to the Administrator for long-range and strategic planning. In the face of the *Challenger* disaster, NASA's new Administrator James Fletcher called for focused examination of American space policy and goals. Fletcher gave that task to Dr. Ride. With the approval of Administrator Fletcher, Ride established the Office of Exploration and began her work with a small group of Headquarters staff members.

She established a workshop that drew individuals from NASA Headquarters, various NASA centers, independent institutes, universities, and a few private corporations. Out of these workshops and discussions at Headquarters, Ride produced *Leadership and America's Future in Space*, published in August 1987. This report stated that America had lost its leadership in space exploration with relation to its presence in low-Earth orbit and with respect to exploring Mars. Worse, the country was at risk of losing pre-eminence in other areas of space exploration.

"Leadership in space does not require that the U.S. be preeminent in all areas of space enterprise," the report stated. "The widening range of space activities and the increasing number of space-faring nations make it virtually impossible for any country to dominate in this way. It is, therefore, essential for America to move promptly to determine its priorities and to pursue a strategy which would restore and sustain its leadership in the areas deemed important."

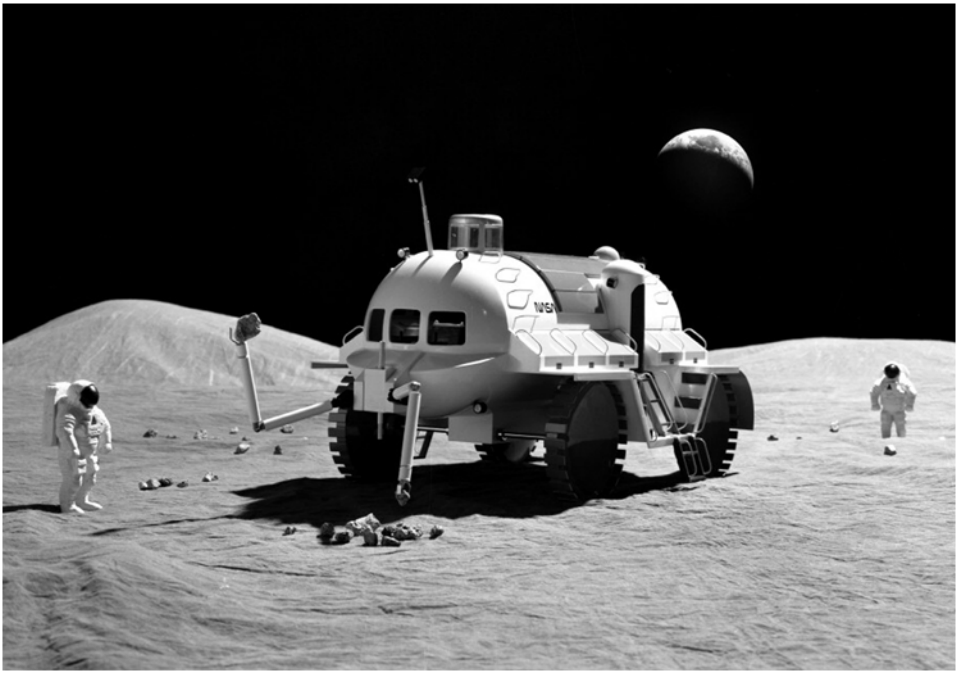
The report called for four bold missions for definition, evaluation and study:

1. Mission to Planet Earth: a program that would use the perspective afforded from space to study and characterize our home planet on a global scale.
2. Exploration of the Solar System: a program to retain U.S. leadership in exploration of the outer solar system, and regain U.S. leadership in exploration of comets, asteroids, and Mars.
3. Outpost on the Moon: a program that would build on and extend the legacy of the Apollo Program, returning Americans to the Moon to continue exploration, to establish a permanent scientific outpost, and to begin prospecting the Moon's resources.
4. Humans to Mars: a program to send astronauts on a series of round trips to land on the surface of Mars, leading to the eventual establishment of a permanent base.

The emphasis of the report was that America must regain and retain its leadership in space exploration. It should pursue not one individual initiative as it did with Apollo, but should demonstrate leadership by pursuing several which would serve the national interest.

Leadership and America's Future in Space came to the attention of President Reagan and his advisors during this tumultuous time in NASA's history. On 5 January 1988, the president signed National Security Decision Directive 293 on National Space Policy. An unclassified Fact Sheet, "*Presidential Directive on National Space Policy*", was released by the White House on 11 February 1988. Significantly, the first paragraph in the Fact Sheet under "Goals and Principles", read: "The directive states that a fundamental objective guiding United States space activities has been, and continues to be, space leadership. Leadership in an increasingly competitive international environment does not require United States preeminence in all areas and disciplines of space enterprise. It does require United States preeminence in key areas of space activity critical to achieving our national security, scientific, technical, economic, and foreign policy goals."

The Directive highlighted three key areas of United States space policy that would receive emphasis:



NASA initiated several studies in the 1990s to examine the new hardware that would possibly be used on the United States' return to the Moon and the establishment of a permanent base. This pressurized lunar surface roving vehicle was one such concept by the Johnson Space Center's Lunar and Mars Exploration Office from February 1990. (NASA)

1. Establish a long-range goal to expand human presence and activity beyond Earth orbit into the solar system.
2. Create opportunities for U.S. commerce in space
3. Continue the U.S. commitment to a permanently manned space station.

The Directive announced the establishment of "Project Pathfinder" for a broad range of manned or unmanned missions, with an initial one hundred million dollar funding request from Congress for technology development. It also outlined a fifteen-point Commercial Space Policy, and addressed other vital U.S. space issues. However, 1988 was a presidential election year, so Congress and the space community took a "wait and see attitude" until after the November 1988 presidential election. That year also marked the return to flight for the Space Shuttle. The Shuttle fleet had been grounded for more than two-and-a-half years, until the successful launch of the Shuttle *Discovery* on 29 September 1988.

On 21 July 1989, twenty years after the first Moon landing, a workshop was held at the Johnson Space Center in Houston to bring together some of the key players during Apollo and videotape their comments on the lessons learned about successfully managing such a gigantic program. Participants included Howard W.

Tindall, George E. Mueller, Owen W. Morris, Maxime Faget, Robert R. Gilruth and Christopher C. Kraft. John M. Logsdon, director of the Space Policy Institute at George Washington University, moderated the discussion.

Toward the end of the discussion, Logsdon asked the panel some rather prophetic questions: "How do you do a program that lasts for a long time? Could you capture the spirit, the élan, the excitement of the 1961 to 1972 period, of that program, with a continuing multi-decade program of humans in space?"

Dr. Mueller stated, "What you need is a commitment, a national commitment to a continuing program that doesn't depend upon a spectacular success, but depends upon some results in the economy."

Dr. Kraft answered by saying, "How you can excite an organization or a nation like we did in Apollo again is, in my mind, extremely difficult to do. To try to come up with an event which is going to recapture the imagination of the United States and the world [in the same way as Apollo] I don't think is possible. So, I think George is absolutely right. We have got to take a different tactic which says look, space is extremely important to the economic structure of our country. It is just as important as defense. It is just as important as education. It is an integral part of what we have got to do in this country to remain preeminent, competitive, and technologically ahead."

The Space Exploration Initiative

The day before this symposium in Houston, on 20 July 1989, President George H. Bush, the former Vice President under Ronald Reagan, announced the Space Exploration Initiative on the steps of the Smithsonian's National Air and Space Museum. In this speech he called for " ... a long-range continuing commitment. First, for the coming decade, for the 1990s, Space Station Freedom, our critical next step in all our space endeavors. And next, for the next century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars. Each mission should and will lay the groundwork for the next."

Vice President Dan Quayle was given the task of leading the National Space Council to formulate the ambitious plan to accomplish this in terms of time, technology and funds. NASA Administrator Richard Truly directed Aaron Cohen, head of the Johnson Space Center, to produce a ninety-day study that would define these major elements of the SEI. Truly presented the *Report of the 90-Day Study on Human Exploration of the Moon and Mars* to Vice President Quayle and the NSC in November 1989. The report outlined the missions, robotics, space transportation, surface systems, Earth-to-orbit transportation, Space Station Freedom, telecommunications, navigation and information management, human needs, science and technology elements. Interestingly, the report specifically called for robotic rovers for Martian exploration:

> "On Mars, a rover with local access to the vicinity of its landing site will perform a preliminary characterization of the martian [sic] surface material composition, mineralogy, and petrology. This characterization will calibrate

> and validate the regional and local geological data from prior orbital missions. The rover will examine, *in situ*, a variety of biochemical and environmental indicators of ancient life-forms. The rover will also play a vital role in directing resource assessment of the site for subsequent manned landings."

The Space Exploration Initiative was as expensive as it was ambitious. The report's estimated cost of SEI spread over a twenty- to thirty-year period was close to 500 billion dollars. It was a staggering figure, and Vice President Quayle and the NSC realized that this plan had to be assessed. Nevertheless, the report made its way to the print media, and it was predictably attacked. The U.S. Congress viewed SEI as overtly ambitious and prohibitively expensive. At the advice of his Vice President and the NSC, President Bush established a new committee, headed by Norm Augustine, to reassess the SEI and make recommendations for realistic implementation of America's future space exploration goals. The *Report of the Advisory Committee On the Future of the U.S. Space Program* was presented to the Vice President in December 1990. The twelve distinguished committee members had heard testimony from over 300 individuals, both inside and outside space industry and from all walks of life. From the Executive Summary, the Committee wrote:

> "The question thus becomes one of what can and should the U.S. afford for its civil space endeavors in a time of unarguably great demands right here on Earth, ranging from reducing the deficit to curing disease and from improving education to eliminating poverty. The answer to this question is made all the more difficult because the space program touches so many aspects of our lives and contributes to the accomplishment of goals ranging from improving education to enhancing our standard of living and from assuring national security to strengthening communications among the peoples of the world. The space program produces technology that enhances competitiveness; the largest rise and subsequent decline in the nation's output of much needed science and engineering talent in recent decades coincided with, and some say may have been motivated by, the build-up and subsequent phase-down in the civil space program."

The Committee unequivocally did not support the plans for massive increases in NASA funding for a return to the Moon and for future manned exploration Mars. It recommended Mission to Planet Earth and Mission from Planet Earth to emphasize Earth and space sciences, a scaling back of the design of the Space Station and a "go-as-you-pay" strategy of manned exploration in returning to the Moon, and eventual missions to Mars. It did recommend, however, the development of Shuttle-derived heavy-lift launch vehicles with the inherent capability of getting cargo and crews to the Moon – something the Shuttle was incapable of doing. The Committee report was indeed broad in its assessment of America's current and future space capabilities, but the clear emphasis was on low-Earth orbit space activities.

America at the Threshold

Nevertheless, there was yet another comprehensive evaluation of America's space program underway at the same time, this being conducted by The Synthesis Group

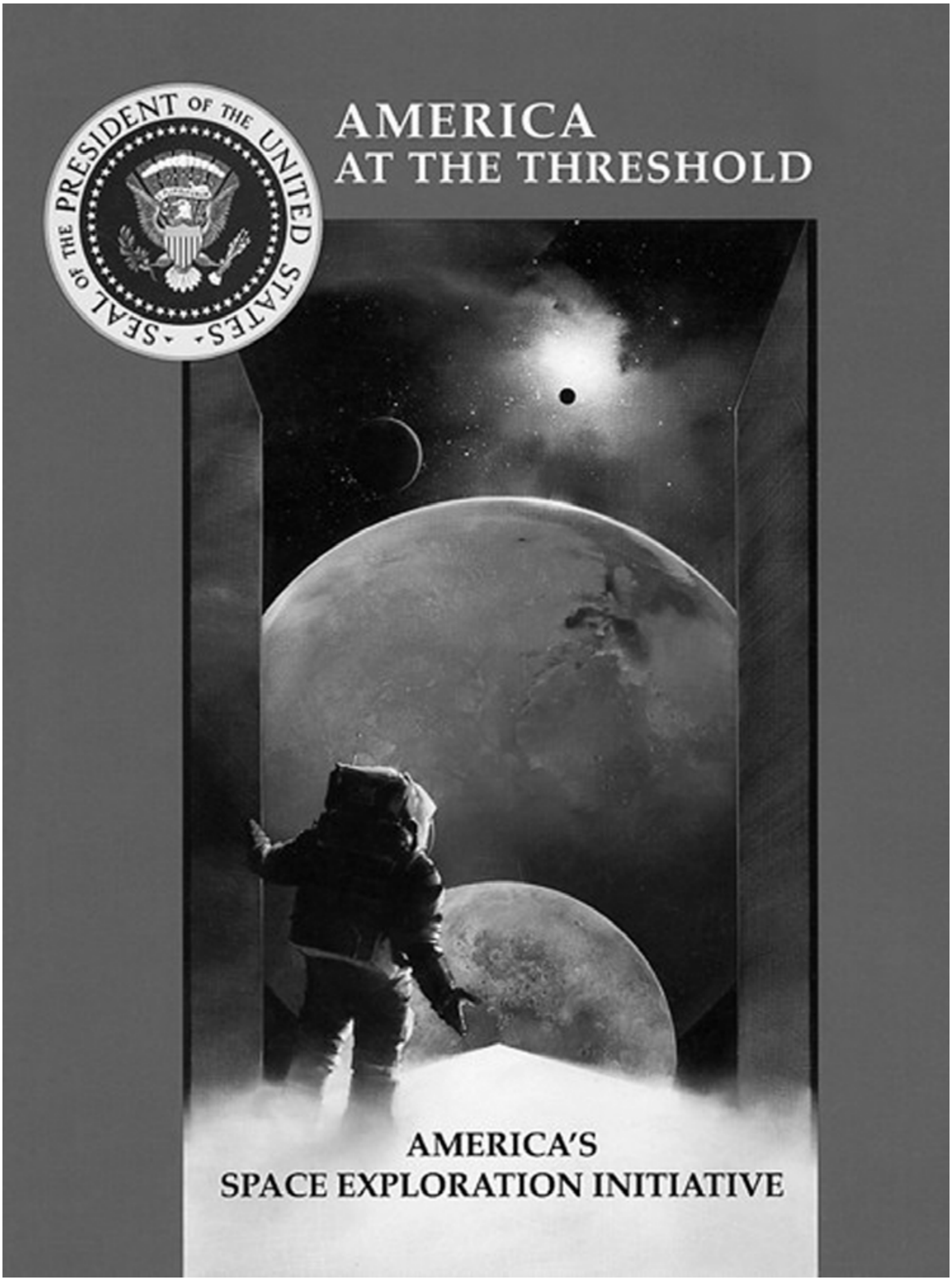
chaired by Gemini and Apollo astronaut Thomas P. Stafford. This group sought the input from a much broader range of individuals, corporations and advocacy groups from all across the United States, which was called the Outreach Program. The results of this study, *America at the Threshold: America's Space Exploration Initiative,* were published in May 1991. Its emphasis was decidedly different from the report produced by Norm Augustine's committee. *America at the Threshold* proclaimed the essential national need to establish a permanent lunar base and to use that to support the eventual goal of launching missions to Mars. The report issued the following recommendations:

- Establish within NASA a long-range strategic plan for the nation's civil space program, with the Space Exploration Initiative as its centerpiece.
- Establish a National Program Office by Executive Order
- Appoint NASA's Associate Administrator for Exploration as the Program Director for the National Program Office.
- Establish a new, aggressive acquisition strategy for the Space Exploration Initiative.
- Incorporate Space Exploration Initiative requirements into the joint NASA-Department of Defense Heavy-lift Program.
- Initiate a nuclear thermal rocket technology development program.
- Initiate a space nuclear power technology development program based on the Space Exploration Initiative requirements.
- Conduct focused life science experiments.
- Establish education as a principal theme of the Space Exploration Initiative.
- Continue and expand the Outreach Program.

In terms of actual hardware, or architecture as it was increasingly being referred to, it outlined the types of heavy-lift launch vehicles that would be necessary to get crews and equipment to the Moon, and the vehicles and facilities that would be placed there. Regarding rovers, it advocated a preliminary unmanned mission to deploy a robotic rover to explore proposed landing sites for manned missions, coupled with an orbiting lunar reconnaissance and mapping probe. Subsequent manned missions included large, heavy, pressurized rovers for long distance exploration, as well as unpressurized rovers for short distance lunar exploration.

Once again, the price tag of all the launch vehicles, cargo ships, shelters, landers and rovers, along with an array of many other kinds of support equipment, was an aspect glossed over in *America at the Threshold.* The Synthesis Group wanted to avoid heated rhetoric over the cost of the ambitious plans outlined, and it succeeded by simply stating the program would be costly, but it would be more costly to America if it did not proceed to seize the moment and begin to implement the plans immediately. In fact, without drastically increased funding, NASA could not begin to implement the programs necessary to get the Space Exploration Initiative literally off the ground.

The recommendation to "Appoint NASA's Associate Administrator for Exploration as the Program Director for the National Program Office" was a very specific one. The Associate Administrator for Exploration at NASA at that time was



America at the Threshold, published in May 1991, was a comprehensive report produced by the Synthesis Group that outlined the Space Exploration Initiative as first proposed by President George Bush. SEI was criticized for its prohibitive cost. (NASA)

Dr. Michael Griffin (he would temporarily leave NASA in 1993). Griffin had worked to put the lunar portion of SEI on a sound technological footing by proposing the First Lunar Outpost (FLO) program. This involved less complex lunar surface hardware, the duration of the missions were shorter, and it naturally used all of NASA's facilities for launch vehicle preparation and launch.

The development and manufacture of the launch vehicle was, in fact, the largest single-line item in the FLO budget. The heavy-lift booster to be used was that proposed by the Synthesis Group, one that rivaled the Saturn V in its lift capability. The launch vehicle was called the Comet, and was over 124 meters tall – considerably taller than the 110-meter Saturn V. The first stage employed five uprated Rocketdyne F-1 engines, the F-1A, and would be aided by two strap-on boosters having two F-1A engines each. The second stage used six J-2S engines and the third (Trans-Lunar Injection) stage employed a single J-2S engine. The lunar lander was much larger and in fact included the Command Module as part of the design. A new lunar roving vehicle would accompany the astronauts to the lunar surface, but illustrations in the FLO presentation showed images of the LRV from Apollo. Comet would be transported to Launch Complex 39 on a reconfigured launch platform, with a Launch Umbilical Tower similar in design to that used with the Saturn V and the crawler transporter.

The FLO proposal was unveiled in August 1992. Testifying before Congress, Griffin stated that the program would cost approximately $25 billion. To get the program going would, of course, require Congressional funding, but the presidential election was coming up that November and there was little hope of even initial funding that year. President Bush lost his re-election bid to Bill Clinton, and those within NASA did not hold out much hope for support for FLO from the new Democratic president. Their belief was well-founded. President Clinton showed virtually no interest in America's space program and the proposals to get the United States back to the Moon languished on shelves. Richard Truly left NASA as Administrator in 1992, and Daniel Goldin took over the helm. Goldin had less grandiose ideas for NASA's future and felt that robotic probes were most cost-effective in the exploration of space. He closed down the Office of Space Exploration in March 1993 and Michael Griffin left NASA (though, interestingly, he would return one day as NASA's eleventh Administrator). The hope of American manned space exploration beyond low-Earth orbit was now all but dead for the rest of the decade. NASA moved forward with the construction of what was now the International Space Station (ISS), its Martian robotic exploration programs, continuing the Hubble Space Telescope program, and of course on-going Space Shuttle missions. The first two modules of the ISS were launched in 1998, but the original grand scope of the ISS had been scaled down considerably in an effort to curb its spiraling cost.

Patience and persistence

The dream of renewed human exploration of the Moon never really died at NASA, however, and in the late 1990s, there was a new effort to examine a return to the Moon and what was realistically necessary to send crews to Mars. Just as important

were the reasons to justify why the United States should do this, all the while remembering the failed attempts to do so since the early 1980s. A small group of lunar and planetary exploration adherents was formed at NASA in 1999, calling themselves the Decadal Planning Team (DPT). While the group was new, several of its members had been architects of previous NASA studies, including *Leadership and America's Future in Space* and the Space Exploration Initiative. The plans being formulated by the DPT were ''science-driven and technology-enabled.'' That is, science was the basis for exploration in the first place, and current technology or soon-to-be-developed technology would be used to determine mission capability. A third component of the scenario being formulated by the DPT was the use of robots to complement human activities in space. Lifting a page from the Augustine Report, this human exploration program was to be, as they called it, ''budgetarily neutral.'' That meant no extraordinary appropriated funds would be given to this new NASA mission directive, and it would have to evolve within the budget the space agency was given annually. Despite the operation of the Space Shuttle and the on-going construction of the ISS, this was to be a multi-year, even a multi-decade effort. Research, engineering, development and construction of the necessary hardware would be stretched out over some considerable time.

The November 1999 presidential election marked another political change in Washington. Bill Clinton had served two terms as President having expressed virtually no interest either in NASA or America's space program. His Vice President, Al Gore, ran against Texas governor George W. Bush, son of the former President. Bush's election marked a change in terms of Presidential support for NASA and its effort in space. Dan Goldin left NASA as its Administrator in 2001 and President Bush appointed Sean O'Keefe from the Office of Management and Budget to get a grip on NASA's budget in general, and ISS costs in particular. The DPT did meet with O'Keefe and he was supportive of their efforts.

By 2002, the DPT had evolved into the NASA Exploration Team, known by the acronym NEXT. The group proposed what it called the NEXT Design Reference Mission, which encompassed five escalating steps. These included: 1) Earth and Low-Earth Orbit, 2) Earth's Neighborhood, 3) Accessible Planetary Surface, 4) Sustainable Planetary Surface, and 5) Go Anywhere, Anytime. It covered not only missions to the Moon and Mars, but even to Jupiter's moon, Callisto. An illustration for this mission showed an astronaut on Callisto's surface, driving a tractor-like rover, assisted by a robonaut, with Jupiter majestically in the distance. It was worthy of being on the cover of any science-fiction magazine. NEXT unveiled it's Design Reference Mission at the 2002 World Space Congress, but it got surprisingly little press and practically none in the national media. It was, however, discussed in several aerospace industry-related publications. Nevertheless, it was still not a part of NASA's future missions.

Another tipping point in America's space program was about to occur that would ultimately redirect NASA's missions and goals and would bring to fruition the years of planning and proposals that had occurred over the previous two decades. On 1 February 2003, the Space Shuttle *Columbia* re-entered the Earth's atmosphere after a fifteen-day mission. The Shuttle and its crew, however, were doomed. During

launch, a large piece of the bipod foam ramp broke off from the main propellant tank and struck *Columbia's* left wing. This caused a breach in the orbiter's Thermal Protection System and during re-entry, the superheated air burned through this breach to the spacecraft's superstructure and progressively weakened and then melted the aluminum. The damage was catastrophic and *Columbia* broke up and disintegrated over Texas during its flight path to Kennedy Space Center in Florida. The seven-member crew perished. The crew of STS-107 included commander Rick Husband, pilot William McCool, payload commander Michael Anderson, mission specialists David Brown, Kalpana Chawla and Laurel Clark, and payload specialist IIan Ramon of Israel.

This was the second Shuttle disaster to result in the loss of the entire crew. On 28 January 1986, *Challenger* blew up 73 seconds after leaving the pad, killing the crew of commander Francis Scobee, pilot Michael Smith, mission specialists Ronald McNair, Ellison Onizuka and Judith Reznik, and payload specialists Gregory Jarvis and Crista McAuliffe, who was a teacher. Now, in 2003, the nation was once again shocked by and in mourning for the loss of another Shuttle crew. The United States had lost fourteen astronauts flying aboard the Space Shuttle and critics were quick to point out that no astronauts had died during all the missions of Mercury, Gemini or Apollo. The crew of Apollo 1 (Gus Grissom, Ed White and Roger Chaffee) had died during a test of the Apollo capsule while the Saturn I-B was on the pad. The Shuttle fleet had been flying for nearly a quarter of a century, and many knowledgeable aerospace engineers, as well as those inside and outside the space exploration community, now called for retiring the Shuttle fleet. It was a serious time of introspection for NASA. When the Columbia Accident Investigation Board issued its report in August 2003, one of its recommendations was a new vehicle to complement or replace the Space Shuttle. NASA had, in fact, already been exploring replacements for the Shuttle but had not initiated the program to actually build them.

The year 2003 was a turning point in many ways for NASA. That year saw a complete review of what NASA should be doing in space begin to take place in Washington. It coincided with policy makers' ideas within the White House and NASA's bureaucracy. Out of the *Columbia* tragedy would come a new program of space exploration beyond Earth orbit, both human and robotic. Administrator O'Keefe recognized that the Shuttle would eventually have to be retired and replaced, but this could not be done immediately. NASA had obligations to its international partners to complete the ISS. In addition, there was nothing that could immediately replace the Shuttle. Still, something new, something much more capable of going beyond low-Earth orbit, and something much safer needed to be developed. NASA also needed a completely new direction and plan for its future. NASA, the White House and policy makers in Washington quietly worked on such a plan. The complete story of how that plan evolved will be the subject of future historians, but the years of studies, proposals and grandiose mission concepts would now bear fruit.

THE VISION FOR SPACE EXPLORATION

On 14 January 2004, President George W. Bush announced the New Vision for Space Exploration at NASA Headquarters. In his opening remarks, the president cited the successes of America's space program over the previous two decades but stated that the country had to resume its manned exploration of space.

"Yet for all these successes, much remains for us to explore and to learn," President Bush stated. "In the past thirty years, no human being has set foot on another world, or ventured farther upward into space than 386 miles – roughly the distance from Washington, D.C. to Boston, Massachusetts. America has not developed a new vehicle to advance human exploration in space in nearly a quarter-century. It is time for America to take the next steps.

"Today I announce a new plan to explore space and extend a human presence across our solar system. We will begin the effort quickly, using existing programs and personnel. We'll make steady progress – one mission, one voyage, one landing at a time."

In January 2004, President George W. Bush announced the New Vision for Space Exploration at NASA Headquarters. The President's Commission on Implementation of United States Space Exploration Policy held public meetings in major cites around the U.S. to garner public opinion and suggestions. The Commission's report, *A Journey to Inspire, Innovate and Discover*, was used by NASA to redirect its space exploration priorities within its operating budget and set America on a course back to the Moon and eventually on to Mars. (NASA)

The president went on to state that the United States intended to complete the International Space Station by 2010 and meet its obligations to its international partners. To do so, the Shuttle had to be returned to flight according to the recommendations of the Columbia Accident Investigation Board. The Shuttle's chief purpose would be to complete the ISS by 2010, and then the Shuttle would be retired. The second goal the president announced was to develop and test a new spacecraft – the Crew Exploration Vehicle. While it would be capable of docking with the ISS, its primary goal was to take crews to the Moon and later to Mars. It would be the first spacecraft of its kind since the Apollo Command Module.

"Our third goal is to return to the Moon by 2020, as the launching point for missions beyond," the president announced with emphasis. "Beginning no later than 2008, we will send a series of robotic missions to the lunar surface to research and prepare for future human exploration. Using the Crew Exploration Vehicle, we will undertake extended human missions to the Moon as early as 2015, with the goal of living and working there for increasingly extended periods. Eugene Cernan, who is with us today – the last man to set foot on the lunar surface – said this as he left: 'We leave as we came, and God willing as we shall return, with peace and hope for all mankind.' America will make those words come true."

President Bush went on to outline the benefits that would come from this new era of human space exploration. He announced the creation of a commission of private and public sector experts to make recommendations to the president and to NASA. He also announced a modest increase in NASA's budget and reallocation of $11 billion of its five-year budget projection to fund the new proposed space exploration goals. Then, drawing from President John Kennedy's speech from 1961, President Bush said:

"Mankind is drawn to the heavens for the same reason we were once drawn into unknown lands and across the open sea. We choose to explore space because doing so improves our lives, and lifts our national spirit. So let us continue the journey. May God bless."

President Bush issued an executive order on 27 January 2004 establishing the President's Commission on Implementation of United States Space Exploration Policy. The Commission would have ninety days to conduct the necessary meetings, hearings and research, collect its findings, and then report those findings to the president through the NASA Administrator within 120 days. The Commission Charter stated that it would examine and make recommendations regarding:

- A science research agenda to be conducted on the Moon and other destinations as well as human and robotic science activities that advance our capacity to achieve the Policy
- The exploration of technologies, demonstrations and strategies, including the use of lunar and other *in situ* natural resources, that could be used for sustainable human and robotic exploration
- Criteria that could be used to select future destinations for human exploration
- Long-term organization options for managing implementation of space exploration activities

- The most appropriate and effective roles for potential private sector and international participants in implementing the Policy
- Methods for optimizing space exploration activities to encourage the interests of America's youth in studying and pursuing careers in mathematics, science and engineering
- Management of the implementation of the Policy within available resources

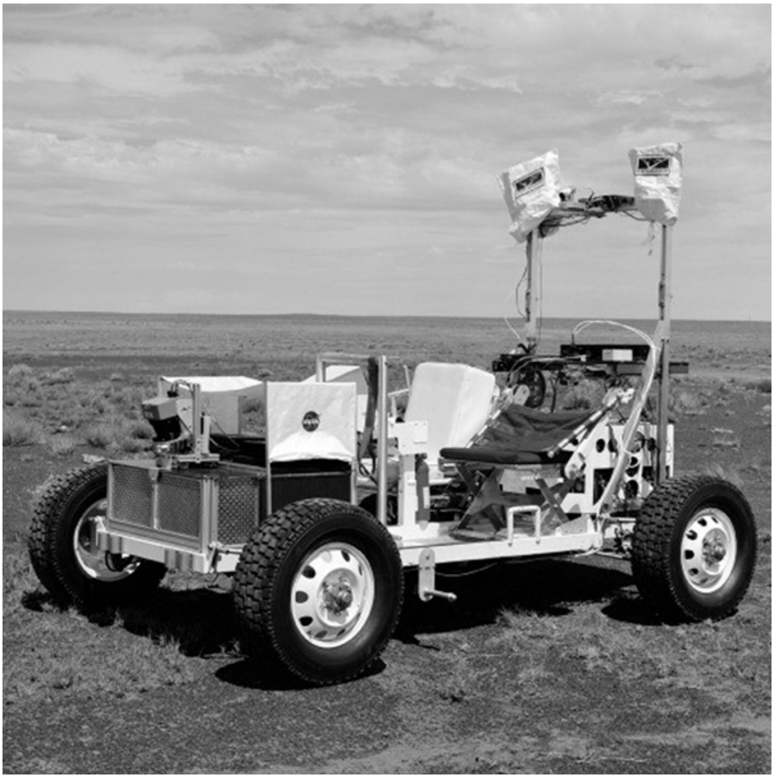
The Commission's plan was to hold public meetings in Washington, D.C., Wright-Patterson Air Force Base in Ohio, Georgia Tech in Atlanta, Georgia, Galileo Academy of Science and Technology in San Francisco, California and the Asia Society in New York City. The Commission would also conduct fact-finding trips to various NASA centers, including the Jet Propulsion Laboratory in Pasadena, California, the Johnson Space Center in Houston, Texas, the John F. Kennedy Space Center in Florida, the George C. Marshall Space Flight Center in Huntsville, Alabama and the Robert H. Goddard Space Flight Center in Greenbelt, Maryland.

From vision to reality

Those who had listened carefully to President Bush's announcement might have gathered that NASA already had a very clear idea of the direction for its future, and that the president's announcement only gave a general outline. In fact, NASA released its very detailed interpretation of its new exploration plan in *The Vision for Space Exploration* published in February 2004. The report was really a blueprint of the Strategic Plan NASA had issued with its budget request around the time of the *Columbia* accident. This was, perhaps, the first document published by NASA that stated the fundamental shift in the agency's exploration priorities from what had transpired for the previous twenty years.

In the *Guiding Principles for Exploration*, the document stated it that would use the Moon as a testing ground for Mars and beyond and that it would start immediately to realign programs and its organization to pursue the Vision as its highest priority. This document described Lunar Testbeds and Missions, Mars Research, Testbeds and Missions, Outer Moons Research and Missions, Extra-solar Planet Research and Observatories, Exploration Building Blocks (launch vehicles, spacecraft, surface shelters, surface vehicles and more), NASA Transformation, Resources (the NASA budget), and the National Benefits of Implementing the Vision. On this last point, the document stated: "Preparing for exploration and research accelerates the development of technologies that are important to the economy and to national security. The space missions in this plan require advanced systems and capabilities that will accelerate the development of many critical technologies, including power, computing, nanotechnology, biotechnology, communications, networking, robotics, and materials. These technologies underpin and advance the U.S. economy and help to ensure national security. NASA plans to work with other government agencies and the private sector to develop space systems that can address national and commercial needs."

In the section titled *Exploration Building Blocks*, it was announced that NASA



Even before the announcement of the Vision for Space Exploration, Johnson Space Center was at work on new vehicles designed to develop technologies for exploring the Moon and Mars. The Science, Crew, Operations and Utility Testbed (SCOUT) is pictured at Meteor Crater, Arizona in 2003. (NASA/JSC)

would initiate Project Constellation to develop the new Crew Exploration Vehicle. Project Constellation would operate out of NASA's Office of Exploration Systems. It would also include development of the Crew Launch Vehicle and other space transportation hardware. NASA exploited the full capabilities of the Internet to get its concepts across to the general public. From the Exploration Systems web page:

> "Constellation is the combination of large and small systems that will provide humans with the capabilities necessary to travel and explore the solar system. Constellation will be made up of Earth-to-orbit, in-space and surface transportation systems, surface and space-based infrastructures, power generation, communications systems, maintenance and science instrumentation, and robotic investigators and assistants."

Project Constellation set the ambitious goal of developing a new CEV and performing the first automated test flight in 2008. This would be a boilerplate version of the CEV to test its systems during the launch boost phase, its Crew Escape

System (much like that of the Apollo capsule) and its landing system on dry land. Unlike Apollo, the CEV would be designed from the outset to land on terrain, with the considerable saving of not having a recovery ship and all its crew at sea. Subsequent test flights of the CEV would test its performance in orbit and then its re-entry system.

The Crew Exploration Vehicle became the hardware driver for the Vision. In March 2004, the Office of Exploration Systems issued its Program Overview, primarily for the major aerospace firms and their subcontractors to learn the design and development requirements and processes NASA anticipated, as well as the long-term program schedule. This was followed in May by a Broad Agency Announcement (BAA) of the *Concept for Exploration & Refinement* at a Pre-solicitation Conference, to familiarize companies with the procedures regarding the competitive bidding process for the CEV and its related systems, and the acquisition strategy through 2008.

The President's Commission on Implementation of United States Space Exploration Policy completed is fact finding and public hearings and published its report, titled *A Journey to Inspire, Innovate and Discover* in June 2004. It was a very carefully drafted report reflecting not only the Commission's findings, but also the experience and expertise of its members, who knew what was at stake for the United States and what the nation must do to accomplish the Vision. The report summarized:

- The space exploration vision must be managed as a significant national priority, a shared commitment of the President, Congress, and the American people
- NASA's relationship to the private sector, its organizational structure, business culture, and management processes – all largely inherited from the Apollo era – must be decisively transformed to implement the new, multi-decadal space exploration vision
- The successful development of identified enabling technologies will be critical to the attainment of exploration objectives within reasonable schedules and affordable costs
- Sustaining the long-term exploration of the solar system requires a robust space industry that will contribute to national economic growth, produce new products through the creation of new knowledge, and lead the world in invention and innovation. This space industry will become a national treasure
- International talents and technologies will be of significant value in successfully implementing the space exploration vision, and tapping into the global marketplace is consistent with our core value of using private sector resources to meet mission goals
- Implementing the space exploration vision will be enabled by scientific knowledge, and will enable compelling scientific opportunities to study Earth and its environs, the solar system, other planetary systems, and the universe
- The space exploration vision offers an extraordinary opportunity to stimulate mathematics, science, and engineering excellence for America's students and

teachers – and to engage the public in a journey that will shape the course of human destiny

The Commission report did make one specific recommendation with regard to America's launch capability. It said, "Although the Commission has not tried to prioritize a list of enabling technologies, we have been particularly concerned that NASA pay close early attention to assessing options for a new heavy-lift space launch capability." A Shuttle-derived heavy-lift launch vehicle was illustrated in the report. This recommendation would be the source of much study within NASA over the next twelve to eighteen months.

The Planetary Society, founded in 1980 in Pasadena, California, and the largest space exploration advocacy organization in the world, issued *Extending Human Presence into the Solar System* in July 2004. The study team of nine members included two co-Team Leaders: Owen K. Garriott, who flew on Skylab 3 and later Shuttle mission STS-9, and Dr. Michael Griffin who would very soon return to NASA as its new Administrator. The Society's report called for the early retirement of the Space Shuttle as soon as possible after meeting its international obligations to the ISS, and accelerating the development of the Crew Exploration Vehicle. Significantly, the report recommended the CEV "... be launched on a new human-rated vehicle, possibly based on the existing Shuttle Reusable Solid Rocket Motor (RSRM), augmented by a new liquid upper stage." The report also called for the development of a Shuttle-derived heavy-lift launch vehicle having a payload capacity of over 100 metric tonnes. When NASA's Advanced Planning and Integration Office issued its Request for Information from its Management Office at the Jet Propulsion Laboratory in November 2004, it did not take long for the Planetary Society's report to be delivered. In fact, NASA was probably already in possession of it. NASA was interested in "... seeking information regarding strategies, mission concepts, investigations, capabilities, and technologies that may enable or enhance NASA's ability to carry out its mission for the nation." NASA planned a Capability Roadmap Public Workshop, to be held later that month in Washington, D.C.

On 15 November 2004, NASA selected seventy proposals, from a total of 485 evaluated, to support the research and technology goals and objectives for the Vision for Space Exploration from the Broad Agency Announcement issued the previous May. This followed study contracts awarded in September to eleven aerospace companies for preliminary human lunar exploration and Crew Exploration Vehicle studies. NASA was indeed breaking out of its low-Earth orbit mode and looking to the Moon and Mars for its exploration future. The first robotic lunar mission under the VSE has already been announced by NASA. Lunar Reconnaissance Orbiter would photographically map the Moon along a circular polar orbit, perform remote sensing, and collect deep space radiation measurements and other important data. It's announced year of launch is 2008, and it will be an invaluable lunar probe used to help decide the most desirable landing sites for future human exploratory missions.

LUNAR AND MARTIAN ROVER PLANNING FOR THE VSE

In the midst of all the larger developments regarding the Vision for Space Exploration, the undeniable need to provide future lunar and Martian exploration crews with rovers had also begun to be addressed. Although the lunar surface had not changed in the previous thirty-two years since American astronauts had driven across it, there were now new mission requirements for these rovers, based on the VSE model and length of stay on the lunar surface. Key issues of LRV configuration, length of operation, durability of components, lunar dust mitigation and long-term power generation were among the factors to be considered.

Future rover requirements and missions

Among the first reports related to rovers since the announcement of the VSE was *Expanding Frontiers with Standard Radioisotope Power Systems*, published in January 2005. Written primarily by scientists and engineers at the Jet Propulsion Laboratory, with contribution from NASA Headquarters, this document looked at the power requirements of lunar and Martian rovers for the future. The original Lunar Roving Vehicle employed rather conventional batteries, which were adequate for the length of the Apollo 15, 16 and 17 missions. The power requirements of future lunar and Martian rovers would be much more demanding. Radioisotope Power Systems (RPS) had been used by the United States for space exploration since 1961. RPS generate electrical power by converting the heat released from the nuclear decay of radioactive isotopes into electricity through any one of a number of conversion processes. These RPS were known for their long life, ruggedness, compact size and reliability. The standard RPS unit used in such successful interplanetary probes as Galileo, Ulysses and Cassini is the General Purpose Heat Source (GPHS) – Radioisotope Thermoelectric Generator (RTG). A new generation of RPS are currently under development, called the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and the Stirling Radioisotope Generator (SRG). These new RPS will have the capability of operating both in the vacuum of space and within a number of different planetary environments. It is these RPS that the report proposed to power future rovers and other surface equipment. Among the first planetary robotic rovers to use this will be the Mars Science Laboratory.

Among the mission vehicle modes considered for use of the MMRTG is the Dual Mode Lunar Roving Vehicle (DMLRV). This was a concept explored during early rover design studies for Apollo by Grumman, Bendix and GM's Defense Research Laboratories. These vehicles were conceived to be operated by astronauts, but with the capability of being remotely and robotically directed. It should be mentioned that the fourth Lunar Roving Vehicle, planned for the eventually-cancelled Apollo 18 mission, was being studied for this conversion from manned to robotic operation. With the return to the Moon, longer lunar missions make the DMLRV a prime candidate as a rover design. The rovers that will operate on the Moon will have to perform for months and even years. They will not be disposable, as the first Lunar Roving Vehicles were, but they will be critical for crews, who cannot go further from their base than the projected walk back constraints – a practically unavoidable

astronaut EVA mandate. In the manned mode, the DMLRV would serve as the primary means of transportation for the crew of two or more astronauts during their exploratory EVAs and performance of scientific experiments. In its robotic teleoperated mode, the DMLRV would be capable of long-range exploration, sending live TV images back to the lunar base for viewing by the astronauts. It would also conduct scientific experiments and take readings, much like the Martian Exploration Rovers have done. The stated mission goal for the DMLRV is "to provide a multipurpose infrastructure element and remote science platform for the exploration of the Moon. The DMLRV would be essential for extending the productivity of human exploration crews, and would provide a unique capability for diverse long-range, long-duration science exploration between human visits. An additional goal of the DMLRV would be to provide a reconfigurable vehicle system capable of conducting surveying and a range of site preparation activities in support of the establishment of permanent human presence on the Moon."

The DMLRV and its systems, like most of the space transportation equipment to be employed in the Vision for Space Exploration, will be designed for years of operational use. The nominal mission length for the DMLRV would be five years. The vehicle would be made up of the four- or six-wheeled rover itself and a two-wheeled trailer containing the MMRTG and a suite of scientific instruments, as well as other equipment. The rover would be powered by rechargeable lithium-ion batteries, with renewable energy provided by the MMRTGs. However, the exposure of the crew and equipment to limited amounts of radiation from the MMRTGs was considered in trade studies. This option of long-term power generation is just one approach for the DMRLV.

The other means of power generation would employ the use of the SRG. These emit lower doses of radiation and have the added benefits of lower heat output and lower mass. The SRG poses less risk to the crew and the equipment and may be the preferred power configuration for the manned DMLRV. Without question, however, is the need for long-term power generation for this vehicle and the use of RPS to meet that mission requirement.

In January 2005, scientists and engineers from NASA's Glenn Research Center presented *Exploration Rover Concepts and Development Challenges* at the first Space Exploration Conference in Orlando, Florida, sponsored by the American Institute of Aeronautics and Astronautics. More than a dozen different rover designs, both unpressurized and pressurized, that had been proposed during the previous ten to twelve years (and some designs that were quite recent) were evaluated. These rovers were conceived to be used on the Moon and Mars. Rovers that had actually been deployed were discussed first, including the Apollo Lunar Roving Vehicle, the Soviet Lunokhod robotic rovers, the Mars *Sojourner* and the Mars Exploration Rovers, *Spirit* and *Opportunity*. The Apollo LRV, of course, was the only manned rover ever to be driven on the Moon. In many ways, the report echoed similar studies produced decades before. Several of the designs were the product of universities. Boeing revisited the rover concept in 1990 with its *Advanced Civil Space Systems Piloted Rover Technology Assessment Study*. In this study, Boeing proposed an unpressurized Light Utility Rover, practically identical to the LRV it built for Apollo 15, 16

and 17, with the addition of a two-wheeled trailer. It also proposed a pressurized rover.

Pressurized or unpressurized rovers?

The authors of the Glenn Research Center document described in detail why a pressurized rover would one day have to be considered. Long-duration missions on the Moon and Mars would of necessity need to provide the astronauts with protection against radiation, as well as offering the advantage of operating and living in the vehicle without constantly having to wear the EVA suit. Unpressurized rovers would be ideal for single-day EVAs that would require the return to the lunar base crew module, whereas longer exploration missions would require pressurized rovers that would permit crews to venture tens or even hundreds of kilometers from the lunar base. Most of the pressurized rover designs employed a cylindrical body with spherical end bulkheads but their power systems varied from solar arrays with batteries, to the use of fuel cells, or the use of some form of RPS. Many designs recognized the need for each wheel to be individually driven. Wheels were the overwhelming choice for supporting and driving the vehicle over the Lunar or Martian surface, but track designs were also a possibility that was considered.

The authors of the GRC document recognized the severe problem that lunar dust will cause to rover mechanical systems, seals, and other equipment. The dust will also be a concern in keeping all electrical components within their thermal operating envelope. Virtually every component of the rover will have to be designed to withstand the long-term abrasive and corrosive effects of the lunar dust. There is an even greater danger crews will have to cope with on the Moon and Mars, which the GRC report succinctly described:

> "The radiation exposure, with no appreciable atmosphere or magnetic field for protection, can be as high as that of interplanetary space in the solar system. Solar and cosmic radiation concerns will dominate human protection as well as electrical component protection from single-event upsets and hard failures. Degradation of optical components will also be a factor. The rovers will encounter the harsh space ionizing radiation environment: large fluxes of low-energy wind particles, smaller fluxes of high-energy galactic cosmic rays, and occasional intense particle fluxes emitted by solar flares. In addition to the ionizing radiation that reaches the lunar surface, soft x-rays and ultraviolet light are also present in significant quantities."

There are other unknowns in the long-term presence on the Moon or Mars that can affect the durability of components. Here is where the experience gained from the Apollo Lunar Roving Vehicle and the Mars Exploration Rovers can add to the necessary body of information that will contribute to the durability and reliability of future rovers. However, it is most curious that the authors of this extensive document seemingly overlooked the only manned vehicle ever to roam the surface of the Moon. The successful Apollo Lunar Roving Vehicle represents a wealth of proven engineering that should be drawn upon for the design of the next generation Lunar Roving Vehicle. Doing so would shed light on why some sub-system design

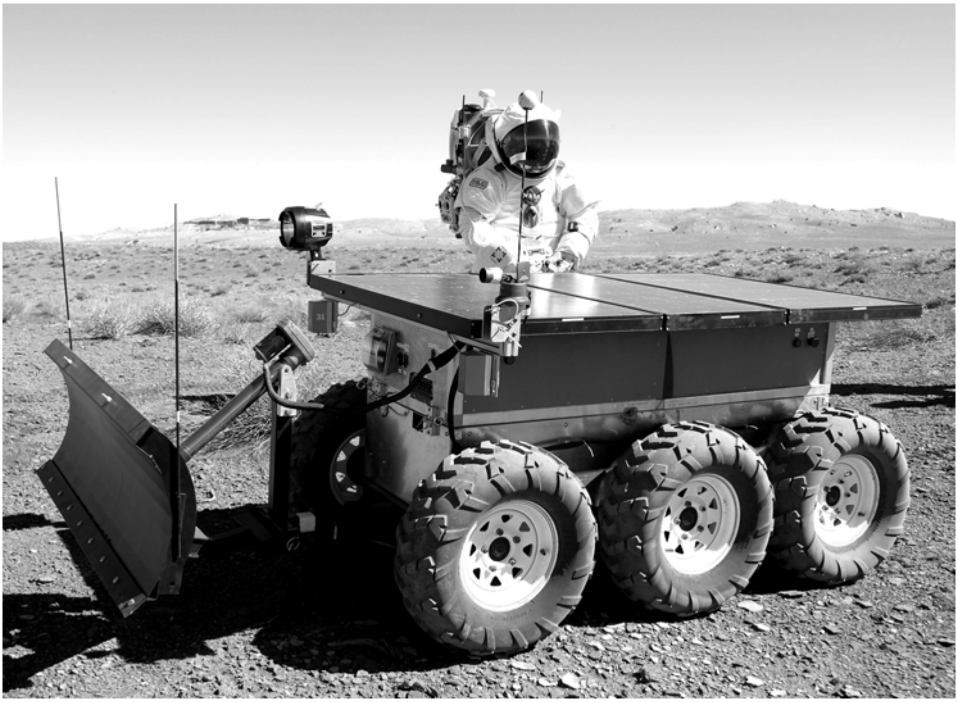
concepts were considered and later discarded, thus avoiding unnecessary trial and error. System performance evaluation of LRV surface activity should be conducted, together with post-mission analysis, in order to contribute this body of knowledge to the next LRV. There have been dramatic advances in the areas of metallurgy, plastics, electronics, mechanisms, power generation, communications and vision systems since Apollo that would vastly improve the LRV's performance and long-term reliability and enhance the safety of its crew.

Pressurized rovers have always been the preferred choice of lunar and planetary exploration planners. There is no lack of clever design and sophisticated appearance and their theoretical advantages are well known. So, too, are their primary disadvantages. For example, they are prohibitively large and heavy. It took a launch vehicle the size and power of the Saturn V to get the small and somewhat cramped Lunar Module to the surface of the Moon. The LM was the literal embodiment of form following function and the Saturn V first stage F-1 engines had to be up-rated in order to get the improved Lunar Module (with the capability to stay on the lunar surface for three days and take the LRV with it to the surface) off the ground. Future lunar modules will, of necessity, be even larger and heavier, and they will certainly take an unpressurized LRV on the early missions. The weight of each and every component that must be boosted to low-Earth orbit and then on to the Moon must be as minimal as engineering and technology can make it. Large pressurized rovers could only be assembled from modules or subassemblies launched separately, they are much too large and heavy to be launched on proposed heavy-lift launch vehicles because of the primary spacecraft and stages that would have to be launched as well. Because of these constraints, pressurized rovers will not likely be employed in the first missions that return to the Moon, but they are, in one form or another, certainly in the future of long-duration lunar and Martian exploration.

Field testing new technologies

NASA has been conducting field tests of vehicles and the next generation EVA suits that will be employed when astronauts first return to the Moon. The Science, Crew, Operations and Utility Testbed (SCOUT) was developed by Johnson Space Center to explore advanced technologies that would be employed by future lunar and Martian vehicles in support of missions. This program began as a fuel cell development program, an alternative to using relatively conventional batteries on a robotic rover testbed, but it soon became an effort to develop a fully-fledged rover testbed as a mobile platform. Frank Delgado is the project lead for SCOUT.

"What we're doing is developing new technologies and operations concepts that will be directly applicable to future lunar or other planetary rover development efforts," Delgado said. "SCOUT is a lab on wheels that can be driven from onboard, by operators at teleoperation stations, or by the onboard autonomous system. The onboard driving mode is very similar to the one used on the original Apollo Lunar Rover. The teleoperation mode uses teleoperation stations with advanced visualization capabilities that greatly enhance the teleoperators' situation awareness. We routinely teleoperate SCOUT from our base camp located within a couple of miles of the vehicle, but during one of our Arizona tests, we successfully teleoperated SCOUT



Johnson Space Center's Advanced EVA Technology Development Lab is evaluating, as one concept, solar-powered crew support vehicles such as this tractor, which would assist in removing lunar rocks. NASA's Desert Research and Technology Studies (RATS) team conducting the evaluations is led by scientists from JSC and Glenn Research Center. (NASA/JSC/GRC)

from the Johnson Space Center in Houston, Texas, which was over 1,000 miles away. It can also be driven in autonomous mode with the use of the onboard software.

"SCOUT's path planner, obstacle avoidance system, and point-to-point navigation system provide it with the ability to go from point A to point B autonomously while avoiding obstacles that are larger than twelve inches tall and following a path that avoids hazards and keep-out zones. Along with these three driving modes, the vehicle has advanced technologies that will enhance its operational effectiveness. An example is the onboard vehicle power health management system. This will collect information related to the power usage and determine how much further the vehicle will be able to drive before running out of power. If power conservation is required to return back to base camp, the power health management system will be able to automatically turn off individual devices not deemed critical during the return trip. Another useful capability being developed is human following. Human following is performed with a stereo vision system that can recognize what a human looks like. When it finds a human, it will begin to visually track them. The tracking information is tied to the drive system and as the person walks, the vehicle will follow behind them at a safe distance, eight to ten meters.

"In addition to over a dozen advanced technologies that the core SCOUT team is developing," Delgado added, "the SCOUT project is working closely with other projects to develop advanced technologies that will prove useful in future lunar exploration endeavors. These include the Advanced Cockpit Evaluation System (ACES), the Planetary Exploration Geophone System (PEGS), the Ultrawide Band System (UWB), the Planetary Drill Project, and the Experiment and Planning Operations Center (ExPOC). The ACES project has developed a generic cockpit that is being used to teleoperate SCOUT with pinpoint accuracy. The UWB project has developed technology that can provide a vehicle's position without the use of GPS. The planetary drill project is developing a system that can take core samples from locations several hundred feet below the surface, and the PEGS project is developing a system that can map the subsurface. The SCOUT project is also working with various organizations from industry, education institutions, and other NASA centers that are also developing technologies that will prove important during future lunar and planetary rover development efforts."

Working closely with this development program is NASA's Desert Research and Technology Studies (RATS). Under the direction of Joe Kosmo at the Johnson Space Center, the Desert RATS have been conducting tests and evaluations of next generation EVA suits, surface equipment and other vehicles. This team includes engineers and scientists from several of NASA's field centers, including JSC, Glenn Research Center and Ames Research Center. Desert RATS include experts from universities such as Carnegie Institute and Virginia Commonwealth University and aerospace industry businesses such as ILC/Dover (manufacturers of NASA's EVA suits) and Hamilton Sundstrand. The majority of the Desert RATS' field testing takes place at various sites outside of Flagstaff, Arizona. Long distance coordination and support is supplied by NASA's Mission Operations Exploration Planning and Operations Center (ExPOC) in Houston, Texas.

"NASA's future involves returning humans to the Moon and to Mars. Field work will be the basic method of operation on these planetary surfaces," Kosmo said. "Field testing prepares and provides a high-fidelity hands-on experience base for engineers and scientists to better design and operate the emerging technologies for planetary surface systems."

One of the cutting edge technologies being developed by Ames Research Center is mobile agent software, also known as personal agent software. This software has been written and is being developed to aid astronauts with robotic vehicles and data collection, first on the Moon and eventually on Mars.

"As you look at NASA's exploration vision to return to the Moon and go on to Mars, human-robotic cooperation will be vital to achieve that vision," according to Eugene Tu, who is deputy director for the Exploration Technology Directorate at Ames Research Center. "In order for human beings to work effectively in extreme environments, such as the Moon and Mars for long durations, astronauts will require the assistance of robotic systems for such tasks as making science discoveries, constructing human habitats, maintaining habitat environments and performing other scientific studies."

The product of NASA's Software, Intelligent Systems and Modeling Program

within the Exploration Systems Mission Directorate, mobile agent software is a continually-evolving technology. For lunar exploration and examination of the regolith, for example, the astronaut would talk to the computer mobile agent software about samples he has discovered. Three key elements of the information the astronaut will convey are the name of the location, which sample bag the astronaut is using to collect the sample, and a description of the sample collected. At the same time, the astronaut will have real-time TV imaging of his collection activity which would both be recorded on the Moon and transmitted back to Earth. Digital still images will also be collected simultaneously, taken by a digital camera mounted on the EVA suit or helmet that may be voice-activated so that the astronaut would not have to use his hands to take the images.

Tests of this software and the Extra-Vehicular Activity Robotic Assistants (ERA) are conducted near Hanksville, Utah, a rugged and arid desert environment perfect for such tests. The capabilities of the ERA are evolving on a year-by-year basis, and will eventually result in the needed performance parameters for first use on the Moon. Those parameters will be used by the NASA center responsible for building the ERA, or they will go into the Request for Proposals issued to outside contractors who will build them for NASA.

The Exploration Systems Architectural Study

Another development at NASA occurred in 2005 that profoundly affected the direction and pace of the Vision for Space Exploration. NASA Administrator Sean O'Keefe had announced his desire to pursue interests in the private sector, and President George W. Bush nominated Dr. Michael Griffin for the role on 14 March 2005. He was confirmed by the U.S. Senate the following month. At the confirmation hearing, Dr. Griffin made positive statements regarding America's role in space and what it meant for the nation.

"In the twenty-first century and beyond, for America to continue to be preeminent among nations, it is necessary for us also to be the preeminent space-faring nation. My conclusion is that we as a nation can clearly afford well-executed, vigorous programs in both robotic and human space exploration, as well as in aeronautics. I believe that, if money is to be spent on space, there is little doubt that the huge majority of Americans would prefer to spend it on an exciting, outward-focused, destination-oriented program. And that is what the President's Vision for Space Exploration is about."

In May 2005, Administrator Griffin requested an Exploration Systems Architectural Study (ESAS) of the best hardware and facilities required to fulfill the Vision for Space Exploration. The preliminary report was issued in September of that year and the final report, nearly 800 pages long, was presented in November. This report detailed the configuration of the Crew Exploration Vehicle (CEV), the Crew Launch Vehicle (CLV) that would employ a modified Shuttle RSRM with a liquid fuel upper stage, and the Cargo Launch Vehicle (CaLV). The CaLV features a liquid fuel core booster and upper stages with two five-segment SRBs. The first stage was originally proposed to be powered by five Space Shuttle Main Engines (SSME) but NASA may also consider using five RS-68 engines (the Rocketdyne RS-68 is

Dr. Dean Eppler, a geologist at the Johnson Space Center, is shown wearing a Mark III EVA suit and operating the controls of Matilda, another robotic testbed vehicle, during tests near Flagstaff, Arizona conducted by the Desert RATS. (NASA/JSC/GRC)

used on the Boeing Delta IV). The Mobile Launch Platforms used for launching the Space Shuttle would be reconfigured to accommodate launching either the CLV or the CaLV from either Launch Complex 39A or 39B at the Kennedy Space Center.

The ESAS report also detailed the Earth Departure Stage that would take the CEV, the Lunar Surface Access Module, (LSAM) and other equipment to the Moon. The need for modular components was outlined and broken down into three weight classifications: Less than 2,000 kg, 2,000 to 10,000 kg, and greater than 10,000 kg. An unpressurized rover was classed in the less than 2,000 kg class, requiring no modular design or assembly on the Moon, while the pressurized rover was classed at over 10,000 kg and would require such options. The pressurized rover came under considerable scrutiny in this report due to the problems involved in getting the components to the lunar surface and their subsequent assembly, as the ESAS report stated:

- After severing all power, data, fluid, and structural connections with the LSAM descent stage, the habitable module must be unloaded from the descent stage (e.g., crane, placed on wheels)
- The habitable volume must be moved to the vicinity of the pressurized rover chassis
- The habitable volume must be lifted (e.g., crane) and placed onto the chassis, and all required connections must be made – power, data, fluid, structural

- The habitable volume will require all systems (Environment Control and Life Support System, Thermal Control System, etc.) that are required to create a surface habitable volume. This means that duplicate systems will be required between the ascent stage and the habitable volume that is left behind
- The habitable volume's systems must be designed with a significantly longer lifetime than is needed to support sortie missions and must be able to accommodate multiple reuses
- No Earth-based integrated validation of the final configuration will be possible

The report went on to explain other problematic issues with the pressurized rover that strongly weighed against it being employed in the first years of missions returning to the Moon:

> "Firstly, the pressurized rover chassis will probably be designed from lessons learned from the unpressurized rover design after years of operations. Secondly, pressurized rovers are not needed until several years into the lunar surface program; therefore, there will probably not be an element of intense design scrutiny until several years after the LSAM design is underway (or is already developed)."

Employing a pressurized rover would directly impact the design of the LSAM since the habitable volume would be integrated with it. This report did suggest designing the LSAM in such a way that none of the pressurized rover's operational components interfaced with the LSAM. There was still the issue of removing the main components of the pressurized rover from the LSAM and then assembling them on the lunar surface, however. In the final analysis, the ESAS report made it clear that the next generation lunar rover would be unpressurized. While the design of much of the human-rated hardware described in the report took into account its future use in Mars missions, the approach was to gain experience with this equipment during long-duration lunar missions and apply the experience gained to improved hardware applicable to Martian missions.

In the report's Summary and Recommendations, the last two New Projects listed were No. 51 for surface handling, transportation, and operations equipment (Lunar or Mars), and No. 52 for surface mobility. The first diligent engineering work will be devoted to the Crew Exploration Vehicle, the Crew Launch Vehicle, the Cargo Launch Vehicle and Earth Departure Stage, and then the Lunar Lander and its many science experiments. Eventually, the Request for Proposals will be issued for the second-generation Lunar Roving Vehicle. A wealth of engineering data and actual lunar experience with LRVs can be brought to bear on the next, improved lunar roving vehicles and the experience gained from these new vehicles will be applied to the design of the human-rated Martian roving vehicles.

SPACE EXPLORATION AND NATIONAL LEADERSHIP

It took the loss of a second Space Shuttle and its crew, a fundamental shift in NASA's mandate regarding human space exploration, and the support of America's president to finally produce a renewed space program that could actually become a reality. NASA's new Administrator, Dr. Michael Griffin, has aggressively pushed the Vision for Space Exploration as NASA's No. 1 priority. However, to do so, he has had to make difficult decisions regarding its budget and where its money would be spent. He reviewed the nearly 120 projects that were underway within the Exploration Systems Mission Directorate (valued at \$1 billion dollars), cancelled eighty of them and scaled back many of those remaining. In turn, he moved to establish more than twenty new projects led by NASA field centers, to directly support the Vision for Space Exploration and the near-term hardware requirements outlined in the ESAS. This included new research and development of the ablative heat shield for the CEV, lightweight fuel tanks for the launch vehicles, EDS and the LSAM, radiation shielding, hardened electronics, and even research into extracting oxygen from the lunar regolith, among other projects. Other NASA programs on the books were also scrutinized. The scientific community involved with NASA's scientific and exploration projects made known their disappointment and concern regarding cancelled projects, and projects or programs threatened with cancellation.

The Space Foundation saw these developments, and looked at America's space program in general and the Vision for Space Exploration in particular. This prestigious and influential organization produced *The Case for Space*, with contributions from not only its own board members but also from experts across the spectrum of the space industry, geopolitics, military issues and even entertainment. This report is a clarion call for the United States to wake up to the vulnerable position it was in with regard to its leadership in space exploration and aggressively move to restore its once-unquestioned supremacy. It stated that the United States had lost 500,000 jobs in the aerospace industry in the previous fourteen years and during the same period, the U.S. had fallen from third among the world's nations that were graduating scientists and engineers to fifteenth. It stated that the U.S graduates fewer than 60,000 engineers each year, while India graduates 80,000, Japan 200,000 and China more than half a million. In addition, tens of thousands of American aerospace engineers, scientists and researchers retire each year, taking their years of experience with them.

The Case for Space stated that other nations have space programs of their own and that the U.S. should not harbor the belief that its space program could not be surpassed. The report emphasized the countless ways that Americans in particular, and millions of people around the world in general, benefit daily from spin-offs as a result of NASA's human and robotic space programs. It also stated that if America failed to address the educational shortage of scientists and engineers, and did not monetarily support the space exploration programs outlined in the Vision, it would run the risk of losing its position as a superpower and global leader. It stated that the Vision for Space Exploration must become a national priority and that it must be funded accordingly if America was to retain its position among nations exploring

space, and remain an economically strong and technologically advanced country. Dr. Neil deGrasse Tyson, who served on the president's Commission on Implementation of United States Space Exploration Policy and the board of The Space Foundation, made a bold challenge: "Let's double NASA's budget." Dr. Tyson and other aerospace authorities argue that if America is serious in implementing the Vision for Space Exploration, NASA cannot do so aggressively with an annual budget that amounts to less than one per cent of the U.S. federal budget. NASA remains one of the most visible agencies of the United States government, yet it operates at levels far below the funding levels of the 1960s when adjusted for inflation. The dramatic project cancellations by Administrator Griffin prove how stretched the agency is in trying to achieve the Vision for Space Exploration. Inadequate funding will slow progress in achieving the Vision and impact upon other projects and programs that should be implemented.

Despite the budgetary constraints NASA must operate under, the United States has indeed entered a new era of space exploration that will inspire a new generation to pursue careers in aerospace. That new generation will also experience the wonder of men and women landing on the Moon, walking on its surface and exploring it with new rovers and robotic assistants. As the United States formalizes those lunar surface mission profiles, research and development will begin on the new lunar roving vehicles that will accompany crews to unexplored areas of the Moon. The challenges in developing those rovers to survive for extended periods on the Moon will also result in advances in metallurgy, materials development, high performance plastics, electronics and communications, and many other benefits.

The success and pace of progress will depend on the U.S. Congress that funds NASA and the support of future presidential administrations. Other nations can contribute to this new era of space exploration and experience both national prestige and technological and economic benefits as a result. Exploration of space is the dream and untold benefits to mankind will be the fruits of that exploration. Lunar and planetary rovers will be an integral part of those missions of discovery.

Appendix 1: planetary rover missions

APOLLO 15 MISSION OVERVIEW

Apollo 15 (CSM Endeavour and LM Falcon)
Saturn V
1971: July 26-August 7
David R. Scott
James B. Irwin
Alfred M. Worden

12 days 17 hours 12 minutes
Landing site: Hadley-Apennine region near Apennine Mountains.
Landing Coordinates: 26.13224 degrees North, 3.63400 degrees East
(Source: National Space Science Data Center)

3 EVAs of 18 hours, 30 minutes, plus 33-minute Standup EVA. Worden also performed a 38-minute trans-Earth EVA. First mission to carry orbital sensors in service module of CSM. ALSEP deployed. Scientific payload landed on Moon doubled. Improved spacesuits gave increased mobility and stay-time. Lunar surface stay-time: 66.9 hours. Lunar Roving Vehicle (LRV), electric-powered, 4-wheel drive car, traversed total 27.9 km (17 miles). In lunar orbit 145 hours, with 74 orbits. Small sub-satellite left in lunar orbit for first time. 76.6 kg (169 lbs) of material gathered.

APOLLO 15 MISSION REPORT EXCERPT

9.8.3 Lunar Surface Mobility Systems Performance

Lunar roving vehicle: The major hardware innovation for the lunar exploration phase of the Apollo 15 mission was the lunar roving vehicle. Because of geological requirements during surface traverses, time was limited for evaluating the characteristics of the vehicle. However, during the traverses, a number of qualitative evaluations were made. The following text discusses the performance, and the

stability and control of "Rover 1", as well as other operational considerations pertaining to the vehicle.

The manual deployment technique worked very well. Simulations had demonstrated the effectiveness of this technique and, with several minor exceptions, it worked exactly as in preflight demonstrations. The first unexpected condition was noticed immediately after removing the thermal blanket when both walking hinges were found open. They were reset and the vehicle was deployed in a nominal manner. The support saddle, however, was difficult to remove after the vehicle was on the surface. No apparent cause was evident. Additionally, both left front hinge pins were out of their normal detent positions; both were reset with the appropriate tool. After removal of the support saddle, the rover was manually positioned such that "forward" would be the initial driving mode.

Front steering was inoperative during the first extravehicular activity. All switches and circuit breakers were cycled a number of times during the early portion of the first extravehicular activity with no effect on the steering. Subsequently, at the beginning of the second extravehicular activity, cycling of the front steering switch apparently enabled the front steering capability which was then utilized throughout the remaining traverses.

Mounting and dismounting the rover was comparable to preflight experience in $^1/_6$-gravity simulations in the KC-135 aircraft. Little difficulty was encountered. The normal mounting technique included grasping the staff near the console and, with a small hop, positioning the body in the seat. Final adjustment was made by sliding, while using the footrest and the back of the seat for leverage. It was determined early in the traverses that some method of restraining the crew members to their seats was absolutely essential. In the case of Rover 1, the seatbelts worked adequately; however, excessive time and effort were required to attach the belts. The pressure suit interface with the rover was adequate in all respects. None of the preflight problems of visibility and suit pressure points were encountered.

The performance of the vehicle was excellent. The lunar terrain conditions in general were very hummocky, having a smooth texture and only small areas of fragmental debris. A wide variety of craters was encountered. Approximately 90 per cent had smooth, subdued rims which were, in general, level with the surrounding surface. Slopes up to approximately 15 per cent were encountered. The vehicle could be maneuvered through any region very effectively. The surface material varied from a thin powdered dust, which the boots would penetrate to a depth of 5 to 8 centimeters (2 to 3 inches) on the slope of the Apennine Front, to a firm rille soil which was penetrated about 1 centimeter (one-quarter to one-half inch) by the boot. In all cases, the rover's performance was changed very little.

The velocity of the rover on the level surface reached a maximum of 13 kilometers (7 miles) per hour. Driving directly upslope on the soft surface material at the Apennine Front, maximum velocities of 10 kilometers (5.4 miles) per hour were maintained. Comparable velocities could be maintained obliquely on the slopes unless crater avoidance became necessary. Under these conditions, the downhill wheel tended to dig in and the speed was reduced for safety.

Acceleration was normally smooth with very little wheel slippage, although some

soil could be observed impacting on the rear part of the fenders as the vehicle was accelerated with maximum throttle. During a "Lunar Grand Prix", a roostertail was noted above, behind, and over the front of the rover during the acceleration phase. This was approximately 3 meters (10 feet) high and went some 3 meters forward of the rover. No debris was noted forward or above the vehicle during constant velocity motion. Traction of the wire wheels was excellent uphill, downhill, and during acceleration. A speed of 10 kilometers per hour could be attained in approximately three vehicle lengths with very little wheel slip. Braking was positive except at the high speeds. At any speed under 5 kilometers (2.7 miles) per hour, braking appeared to occur in approximately the same distance as when using the 1-G trainer. From straight-line travel at velocities of approximately 10 kilometers per hour on a level surface, the vehicle could be stopped in a distance of approximately twice that experienced in the 1-G trainer. Braking was less effective if the vehicle was in a turn, especially at higher velocities.

Dust accumulation on the vehicle was considered minimal and only very small particulate matter accumulated over a long period of time. Larger particles appeared to be controlled very well by the fenders. The majority of the dust accumulation occurred on the lower horizontal surfaces such as floorboards, seatpans, and the rear wheel area. Soil accumulation within the wheels was not observed. Those particles which did pass through the wire seemed to come out cleanly. Dust posed no problem to visibility.

Obstacle avoidance was commensurate with speed. Lateral skidding occurred during any hardover or maximum-rate turn above 5 kilometers per hour. Associated with the lateral skidding was a loss of braking effectiveness. The suspension bottomed out approximately three times during the entire surface activity with no apparent ill effect. An angular 30-centimeter (1-foot) high fragment was traversed by the left front wheel with no loss of controllability or steering, although the suspension did bottom out. A relatively straight-line traverse was easily maintained by selection of a point on the horizon for directional control, in spite of the necessity to maneuver around the smaller subdued craters. Fragmental debris was clearly visible and easy to avoid on the surface. The small, hummocky craters were the major problem in negotiating the traverse, and the avoidance of these craters seemed necessary to prevent controllability loss and bottoming of the suspension system.

Vehicle tracks were prominent on the surface and very little variation of depth occurred when the bearing on all four wheels was equal. On steep slopes, where increased loads were carried by the downhill wheels, deeper tracks were encountered – perhaps up to 3 or 4 centimeters (an inch or two) in depth. There was no noticeable effect of driving on previously deposited tracks, although these effects were not specifically investigated. The chevron tread pattern left distinct and sharp imprints. In the soft, loose soil at the Apollo lunar surface experiment package site, one occurrence of wheel spin was corrected by manually moving the rover to a new surface.

The general stability and control of the lunar roving vehicle was excellent. The vehicle was statically stable on any slopes encountered and the only problem associated with steep slopes was the tendency of the vehicle to slide downslope when

both crewmen were off the vehicle. The rover is dynamically stable in roll and pitch. There was no tendency for the vehicle to roll even when traveling upslope or downslope, across contour lines or parallel to contour lines. However, qualitative evaluation indicates that roll instability would be approached on the 15-degree slopes if the vehicle were traveling a contour line with one crewmember on the downhill side. Both long- and short-period pitch motions were experienced in response to vehicle motion over the cratered, hummocky terrain, and the motion introduced by individual wheel obstacles. The long-period motion was very similar to that encountered in the 1-G trainer, although more lightly damped. The ‘‘floating’’ of the crewmembers in the $^{1}/_{6}$-G field was quite noticeable in comparison to 1-G simulations. Contributions of short period motion of each wheel were unnoticed and it was difficult to tell how many wheels were off the ground at any one time. At one point during the ‘‘Lunar Grand Prix’’, all four wheels were off the ground, although this was undetectable from the driver’s seat.

Maneuvering was quite responsive at speeds below approximately 5 kilometers per hour. At speeds on the order of 10 kilometers per hour, response to turning was very poor until speed was reduced. The optimum technique for obstacle avoidance was to slow below 5 kilometers per hour and then apply turning correction. Hardover turns using any steering mode at 10 kilometers per hour would result in a breakout of the rear wheels and lateral skidding of the front wheels. This effect was magnified when only the rear wheels were used for steering. There was no tendency toward overturn instability due to steering or turning alone. There was one instance of breakout and lateral skidding of the rear wheels into a crater approximately 0.5 meter (1.5 feet) deep and 1.25 meters (4 feet) wide. This resulted in a rear wheel contacting the far wall of the crater and subsequent lateral bounce. There was no subsequent roll instability or tendency to turn over, even though visual motion cues indicated a roll instability might develop.

The response and the handling qualities using the control stick are considered adequate. The hand controller was effective throughout the speed range, and directional control was considered excellent. Minor difficulty was experienced with feedback through the suited crewmember to the hand controller during driving. However, this feedback could be improved by a more positive method of restraint in the seat. Maximum velocity on a level surface can be maintained by leaving the control stick in any throttle position and steering with small inputs left or right. A firm grip on the handle at all times is unnecessary. Directional control response is excellent although, because of the many dynamic links between the steering mechanism and the hand on the throttle, considerable feedback through the pressure suit to the control stick exists. A light touch on the hand grip reduces the effect of this feedback. An increase in the lateral and breakout forces in the directional hand controller should minimize feedback into the steering.

Two steering modes were investigated. On the first extravehicular activity, where rear-wheel-only steering was available, the vehicle had a tendency to dig in with the front wheels and break out with the rear wheels with large, but less than hardover, directional corrections. On the second extravehicular activity, front-wheel-only steering was attempted, but was abandoned because of the lack of rear wheel

centering. Four-wheel steering was utilized for the remainder of the mission. It is felt that for the higher speeds, optimum steering would be obtained utilizing front steering provided the rear wheels are center-locked. For lower speeds and maximum obstacle avoidance, four-wheel steering would be optimal. Any hardover failure of the steering mechanism would be recognized immediately and could be controlled safely by maximum braking.

Forward visibility was excellent throughout the range of conditions encountered with the exception of driving toward the zero-phase direction. Washout, under these conditions, made obstacle avoidance difficult. Up-sun was comparable to cross-sun if the opaque visor on the lunar extravehicular visor assembly was lowered to a point which blocks the direct rays of the sun. In this condition, crater shadows and debris were easily seen. General lunar terrain features were detectable within 10 degrees of the zero phase region. Detection of features under high-sun conditions was somewhat more difficult because of the lack of shadows, but with constant attention, 10 to 11 kilometers (5.5 to 6 miles) per hour could be maintained. The problem encountered was recognizing the subtle, subdued craters directly in the vehicle path. In general, 1-meter (3.25-foot) craters were not detectable until the front wheels had approached to within 2 to 3 meters (6.5 to 10 feet).

The reverse feature of the vehicle was utilized several times, and preflight-developed techniques worked well. Only short distances were covered, and then only with a dismounted crewmember confirming the general condition of the surface to be covered.

The 1-G trainer provides adequate training for lunar roving vehicle operation on the lunar surface. Adaptation to lunar characteristics is rapid. Handling characteristics are quite natural after several minutes of driving. The major difference encountered with respect to preflight training was the necessity to pay constant attention to the lunar terrain in order to have adequate warning for obstacle avoidance if maximum average speeds were to be maintained. Handling characteristics of the actual lunar roving vehicle were similar to those of the 1-G trainer with two exceptions: braking requires approximately twice the distance, and steering is not responsive in the 8- to 10-kilometer (4- to 5.5-mile) per hour range with hardover control inputs. Suspension characteristics appeared to be approximately the same between the two vehicles and the $^{1}/_{6}$-G suspension simulation is considered to be an accurate representation with the exception of the crewmembers' weight.

The navigation system is accurate and a high degree of confidence was attained in a very short time. Displays are also adequate for the lunar roving vehicle systems.

Lunar communications relay unit: The lunar communications relay unit and associated equipment operated well throughout the lunar surface activities. The deployment techniques and procedures are good, and the operational constraints and activation overhead are minimum. Alignment of the High-Gain Antenna was the only difficulty encountered, and this was due to the very dim image of the Earth presented through the optical sighting device. The use of signal strength as indicated on the automatic gain control meter was an acceptable backup alignment technique.

APOLLO 16 MISSION OVERVIEW

Apollo 16 (CSM Casper and LM Orion)
Saturn V
1972 April 16-27
John W. Young
Thomas K. Mattingly II
Charles M. Duke, Jr.

11 days 01 hour 51 minutes
Landing site: Descartes Highlands.
Landing Coordinates: 8.97341 degrees South, 15.49859 degrees East
(Source: National Space Science Data Center)

First study of highlands area. Selected surface experiments deployed, ultraviolet camera/spectrograph used for first time on Moon, and LRV used for second time. LRV traversed 26.7 km. Three EVAs totaling 20 hours 14 minutes. 95.8 kg (213 lbs) of lunar samples collected. Lunar surface stay-time, 71 hours; in lunar orbit 126 hours, with 64 orbits. Sub-satellite released in lunar orbit. Mattingly performed 1-hour trans-Earth EVA.

APOLLO 16 MISSION REPORT EXCERPT

8.1 Lunar Roving Vehicle

The lunar roving vehicle performance was good; however, several system problems occurred. These problems are:

a. Higher-than-expected battery temperatures
b. Multiple failures of instrumentation hardware
c. Loss of rear fender extension
d. Temporary loss of rear steering.

Procedural errors resulted in the temporary loss of rear drive power and a temporary loss of all navigation displays except heading and speed.

The approximate distances driven during the three extravehicular activities were 4.2, 11.1 and 11.4 kilometers for a total of 26.7 kilometers. Speeds up to 14 kilometers per hour were achieved on the level surfaces. Slopes estimated to be as steep as 20 degrees were negotiated without difficulty.

The lunar roving vehicle provided electrical power for voice, telemetry, and television communications throughout the first two extravehicular activities, and also provided power for television operations after the third extravehicular activity. A total of 98.2 ampere-hours was consumed from the 242 ampere-hours available in the two batteries.

Several minor problems, which subsequently disappeared, were experienced during the activation of the lunar rover. The rear steering was inoperative, the

battery 2 ampere-hours remaining and voltage readings were off-scale low, and both battery temperatures were off-scale low.

After returning to the lunar module near the end of the first traverse, the Commander performed a lunar roving vehicle evaluation while the Lunar Module Pilot took 16-mm documentary motion pictures.

At the conclusion of the first extravehicular activity, the vehicle was parked with the front of the vehicle pointing towards the north. The battery temperatures were 104 degrees F and 105 degrees F with 108 and 105 ampere-hours remaining. The battery covers were brushed and opened, the radiator surfaces were dusted, and the power-down was completed. The battery covers did not close between the first and second extravehicular activities and temperatures at power-up for the second extravehicular activity were 70 degrees F and 82 degrees F.

On the second traverse, the attitude indicator pitch scale fell off, but the needle was still used to estimate pitch attitudes. Incorrect matching of switches caused a loss of rear-wheel power. Correct switch configuration returned the vehicle operation to normal. The crew noted that the forward wheels tended to dig in when attempting to climb slopes without rear-wheel power. The right rear fender extension was knocked off and, thereafter, dust was thrown up from the right rear wheel and covered the crew, the console, and the communications equipment. Mid-way through the second extravehicular traverse, the ampere-hour integrator for battery 1 began indicating about four times the normal battery usage. Because of high-than-desired temperatures on battery 1, a series of procedures were initiated to lower the load. These procedures probably caused the inadvertent removal of drive power from a pair of wheels, thereby losing two odometer inputs and the associated static range, bearing, and distance displays. The problem cleared when the normal switch and circuit breaker configuration was restored.

At power-up for the third traverse, the battery covers were closed manually and the lunar communications relay unit was switched to its own power. The lunar roving vehicle battery temperatures were 102 degrees F and 120 degrees F. About 2 hours after power-up, the caution and warning flag was activated because the battery 2 temperature exceeded 125 degrees F. Rear-wheel drive power and steering were switched to battery 1 bus B. Later, the battery 1 temperature indicator went off-scale low, indicating a meter failure. Both batteries were functional at the end of the third extravehicular activity when the lunar roving vehicle was configured to provide power for television. The closeout reading of the battery 2 temperature was 143 degrees F.

8.2 Lunar Communications Relay Unit and Ground-Commanded Television Assembly

The lunar communications relay unit and ground-commanded television assembly operated for 12 hours 44 minutes during the lunar surface extra-vehicular activities. The relay unit in conjunction with the television camera was energized by up-link command for lunar module ascent television coverage and for six days of scientific lunar surface observations on a once-per-day basis until 30 April 1972. At that time, the system could not be energized by up-link command. Down-link data from the relay unit on the preceding day showed the expected temperatures, internal voltages, and RF signal strength. Possible causes of the problem include: (1) malfunction of

the television control unit up-link decoder due to its pre-launch predicted high temperature condition (above qualification level), and (2) loss of input power because of incorrect circuit breaker configuration on the lunar roving vehicle that would have placed only one of the two batteries on the line.

APOLLO 17 MISSION OVERVIEW

Apollo 17 (CSM America and LM Challenger)
Saturn V
1972 December 7-19
Eugene A. Cernan
Ronald E. Evans
Harrison H. Schmitt

12 days 13 hours 52 minutes
Landing site: Taurus-Littrow
Landing Coordinates: 20.19 degrees North, 30.77 degrees East
(Source: National Space Science Data Center)

APOLLO 17 MISSION REPORT EXCERPT

9.1 Lunar Roving Vehicle

The lunar roving vehicle satisfactorily supported the lunar exploration objectives. Controllability was good, and no problems were experienced with steering, braking, or obstacle negotiation. The navigation system gyro drift and closure error at the lunar module were negligible. All interfaces between the crew and the lunar roving vehicle and the stowed payload were satisfactory.

Deployment of the lunar roving vehicle from the lunar module was smooth and no significant problems were encountered. The chassis lock pins did not seat fully, but the crew used the deployment assist tool to seat the pins.

At the initial power-up, the lunar roving vehicle battery temperatures were higher than predicted; 95 degrees F for battery 1 and 110 degrees F for battery 2 compared to the predicted temperatures of 80 degrees F for each. This was partially due to the trans-lunar attitude profile flown, and partially to a bias in the battery temperature meter. Following adequate battery cool-down after the first extravehicular activity, temperatures for the remainder of the lunar surface operations were about as predicted.

The following lunar roving vehicle systems problems were noted:

a. The battery 2 temperature indication was off-scale low at the start of the third extravehicular activity.
b. The right rear fender extension was knocked off prior to leaving the lunar module on the first extravehicular traverse.

The battery 2 temperature indication was off-scale low at the beginning of the third extravehicular activity. This condition continued for the remainder of the lunar surface operation. The most probable cause was a shorted thermistor in the battery. The same condition was noted on ground testing of two other batteries. Electrolyte leakage through the sensor bond, as a result of elevated temperatures, may have caused the short. Temperature monitoring was continued using battery 1 as an indicator with temperature trends established from data on the first and second extravehicular activities for battery 2.

During the first extravehicular activity at the lunar module site, the Commander inadvertently knocked off the right rear fender extension. While still at the lunar module site, the Commander taped the extension to the fender. Because of the dusty surfaces, the tape did not adhere and the extension was lost. Lunar surface maps were subsequently clamped to the fender. This fix was adequate.

9.2 Lunar Communications Relay Unit and Ground-Commanded Television Assembly
The lunar communications relay unit provided satisfactory support from the lunar surface, and the ground-commanded television assembly produced good quality pictures at all times. Activation was initiated about 1 hour and 11 minutes after crew egress for the first extravehicular activity. Television coverage of crew egress was not available because the capability to televise from the lunar module was eliminated for Apollo 17 to save weight.

The system allowed ground personnel to coordinate lunar surface activities with the crew. The rover fender repair and the deep-core drilling were especially significant in this area. Television coverage, augmented by crew comments, was a valuable asset used in making an early determination of the actual experiment locations, sampling sites, traverse stops, geological features, and the landing point area. Panoramic reproductions of the television pictures were a significant contribution to a preliminary interagency geology report which was issued on 17 December 1972, two days prior to termination of the mission.

The lunar communications system failed to respond to uplink turn-on commands about 36 hours after lunar liftoff. The condition was expected because the lunar environment eventually exceeded the operational temperature limits of the equipment.

Total television operating time was 15 hours and 22 minutes.

MARS PATHFINDER/SOJOURNER MISSION OVERVIEW

Launch Vehicle: Boeing Delta II
Pathfinder Spacecraft Mass: 895 kg
Sojourner Rover Mass: 10.6 kg
Launched: 1996 December 4
Landed: 1997 July 4
Landing Site and Coordinates: Ares Vallis; 19.33 degrees N, 33.55 degrees W
Last Data Transmission: 1997 September 27
(Source: National Space Science Data Center)

Mars Pathfinder primary mission duration was established for 7 sols. It far surpassed this goal. The Pathfinder lander returned more than 16,500 images and the Sojourner rover returned 550 images. The rover performed more than 15 chemical analyses of surrounding rocks and soil, and the lander returned extensive data on the region's weather. Scientific findings from the instruments indicated that region of Mars once had liquid water on the surface and had a thicker atmosphere.

MARS EXPLORATION ROVER (MER) MISSION OVERVIEW

Launch Vehicle: Boeing Delta II
Lander Mass: 348 kg
MER Mass: 174 kg (185 kg on-orbit dry mass)
MER *Spirit* Launched: 2003 June 10
Landing Site and Coordinates: Gusev Crater; 14.57 degrees S, 175.47 degrees E
MER *Opportunity* Launched: 2003 July 7
Landing Site and Coordinates: Meridiani Planum; 1.95 degrees S, 354.47 degrees E
(Source: National Space Science Data Center)

The Mars Exploration Rovers' primary mission duration was established for 90 sols. They far surpassed this goal. *Spirit* and *Opportunity* continued to operate past 900 sols. NASA repeatedly extended the missions of these rovers and provided operating funds to JPL to perform on-going mission operations. Both rovers returned irrefutable scientific evidence of the previous presence of water. They also returned unprecedented data on Mars' weather and composition of soils and rocks. The rovers also validated mechanical and electrical systems for mission longevity.

Appendix 2: The Lunokhods – Russia's marvelous robotic rovers

By Ronald A. Creel

In the fall of 1971, Apollo Lunar Roving Vehicle (LRV) thermal control engineers were applying experiences from the successful use of the first LRV during the Apollo 15 mission, and preparing for the next Moon exploration mission. A very interesting document was delivered to me as one of the LRV thermal engineers. This document was an unexpected English translation describing the Russian "Lunokhod-1, Mobile Lunar Laboratory". Myself and others at NASA had been remotely following American space trade magazine reports about the parallel Russian exploits in Moon exploration, especially their highly successful first "extra-terrestrial" Lunokhod (Moonwalker) robotic rover in 1970.

Consideration had been given to converting the fourth LRV for robotic operation, after manned use, for the ultimately cancelled Apollo 18 mission. I was very interested in gaining more information about how the Russians had been able to develop their robotic rover, which survived the higher and then much lower temperatures during full temperature cycles on the Moon. In the translated document was a complete description of how the Russians had used a radioisotope heat source to maintain electronics temperatures in their remotely-operated rovers during the fifteen dormant eclipse days without solar heating and very cold lunar surface temperatures.

Many years later, E-mail discussions with my counterpart rover engineers in Russia led to an invitation for me to attend a robotic rover conference at the Lunokhod development facility in St. Petersburg, Russia, in October 2004. I shared the Apollo rover thermal control experiences and learned much about the Lunokhod experiences from the very informative and sharing Russian engineers. They related how special lubricants were used to allow external exposed motor and drive systems to survive, and how the nuclear heat source kept the electronics "alive". The Russian engineers showed me the smaller rover, with walking "skis" instead of wheels, which

they had tried to land on Mars in 1971. I also accepted a medal from the Russian Cosmonautics Federation on behalf of all of the Apollo and LRV workers.

The Lunokhods were very successful and added greatly to the body of knowledge about lunar mobility and survival. Lunokhod-1 traversed more than 10.5 km during the almost eleven months it was operated on the Moon after its deployment on 17 November 1970. This was well beyond the planned four months of survival and exploration. The radioisotope heater system performed its temperature maintenance function quite well. The faster Lunokhod-2 then traversed more than 34 km on the Moon during a shorter four month period after its deployment on 15 January 1973. The reason for this reduced operating period had intrigued me, until I got a full explanation from one of the original Lunokhod drivers, General Dovgan.

There was a great desire to accumulate more and more daily mileage with Lunokhod-2. It was normally planned to keep the vehicle's protective top lid, with solar cells on the inside, open during the fairly slow (between 0.8 and 2.0 kph) daytime driving around on the Moon. A situation arose in which it was contemplated as to whether or not to proceed down into what looked to be a fairly steep crater. General Dovgan recommended that the lid be closed in order to protect the solar cells before proceeding. This was not the normal written procedure, and, with a recent new personnel shift change having occurred at Lunokhod Mission Control, the lid closing was not approved.

As Lunokhod-2 started down into that crater, it began to slide, and it was decided to immediately reverse its direction as soon as this could be accomplished. As the vehicle was being remotely driven back out of the crater, it hit the side of the crater and a large amount of lunar soil was dumped onto the exposed solar power collecting cells. The lunar soil deposited on the solar cells doomed Lunokhod-2, because it could not be removed, and therefore the needed energy to continue exploration could not be generated. This was similar to the problems which had been encountered with stirred up lunar soil and dust during the Apollo rover missions. Lunar dust was very resistant to being removed from surfaces, and resulted in overheating of several LRV and other components.

Being able to meet and share rover experiences with the Lunokhod engineers was very fulfilling and cathartic for me. After more than three decades, fellow rover designers and engineers could finally discuss challenges and ideas, which had previously been impossible due to political and geographical limitations. More than ever, I was convinced that mitigation of adverse lunar dust effects and nuclear energy sources like those used by the Russians on the Lunokhods (and also on past and future Mars rovers) will be required for future extended survival and operation on the Moon. Now, I anticipate further potential collaboration with my Russian friends on rover projects for the renewed vision for Moon exploration.

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LUNAR ROVING VEHICLE COLLECTION, UNIVERSITY OF ALABAMA AT HUNTSVILLE

The H. Louis Salmon Library at the University of Alabama at Huntsville holds all the papers compiled by Saverio "Sonny" Morea, which he donated after his retirement from the Marshall Space Flight Center. The Lunar Roving Vehicle Collection includes hundreds of memos, letters, faxes, documents, and other materials that Mr. Morea kept during his management of the LRV program at MSFC.

The U.S. Geological Survey, Branch of Astrogeology–A Chronology of Activities from Conception through the End of Project Apollo (1960-1973) By Gerald G. Schaber
URL: http://pubs.usgs.gov/of/2005/1190/

The above Open File Report by Dr. Gerald Schaber is both comprehensive and very entertaining to read. The report itself constitutes years of effort by Dr. Schaber in conducting many one-to-one interviews, researching, compiling, writing and editing. In so doing, he has preserved years of work by the USGS in support of the Apollo program. There are also links to many rare and interesting photographs from this wonderful era, a few of which appear in this book through Dr. Schaber's generosity.

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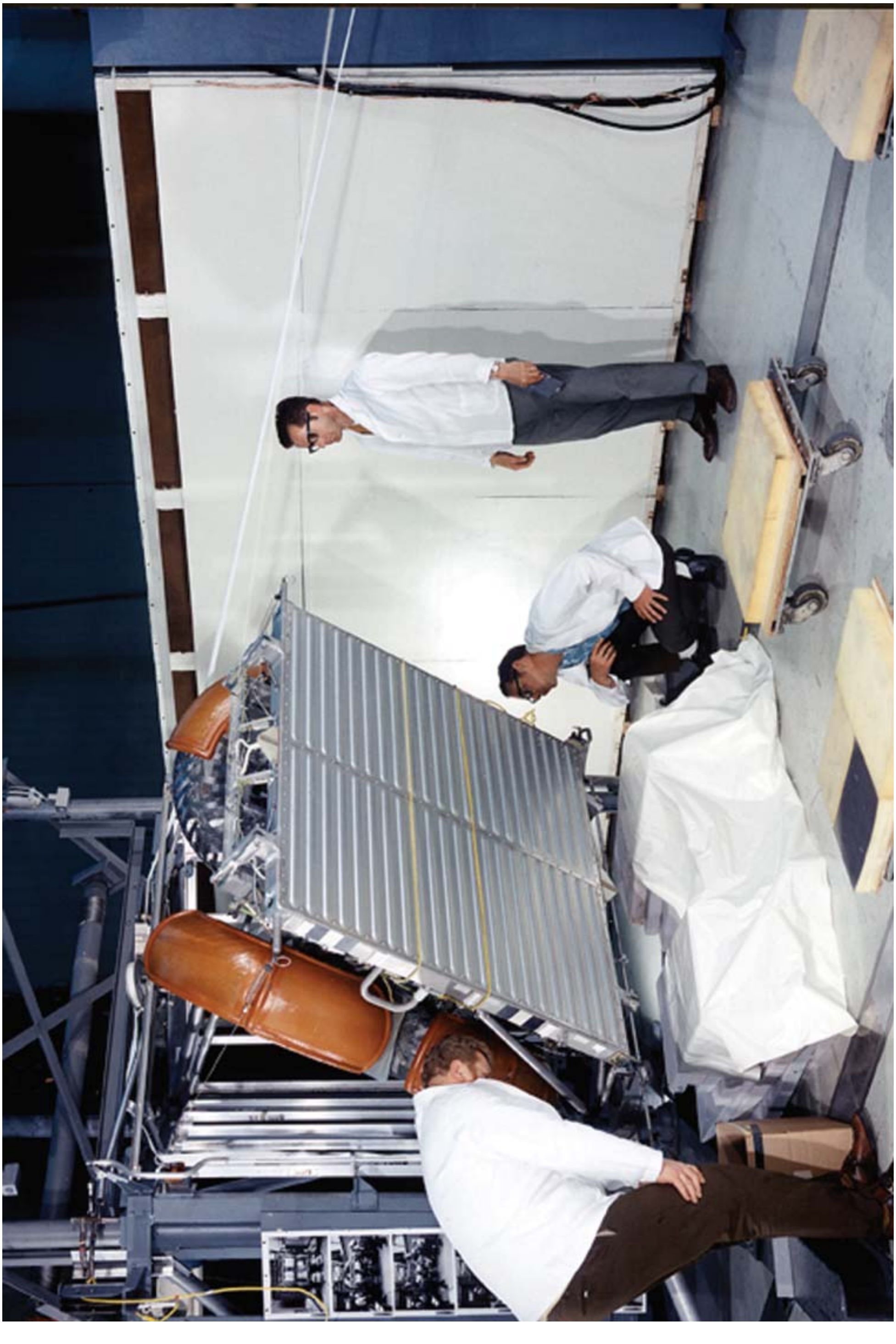
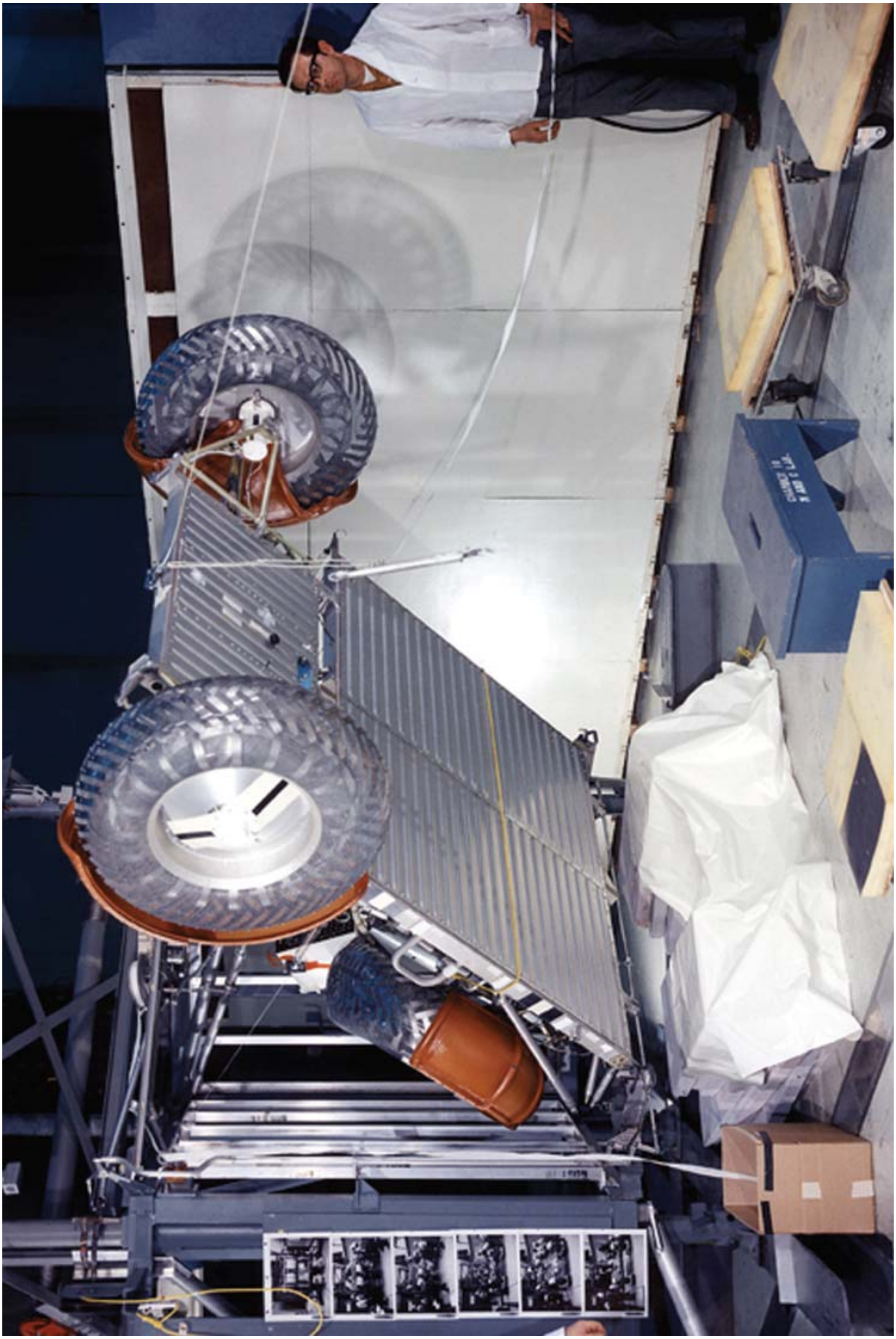
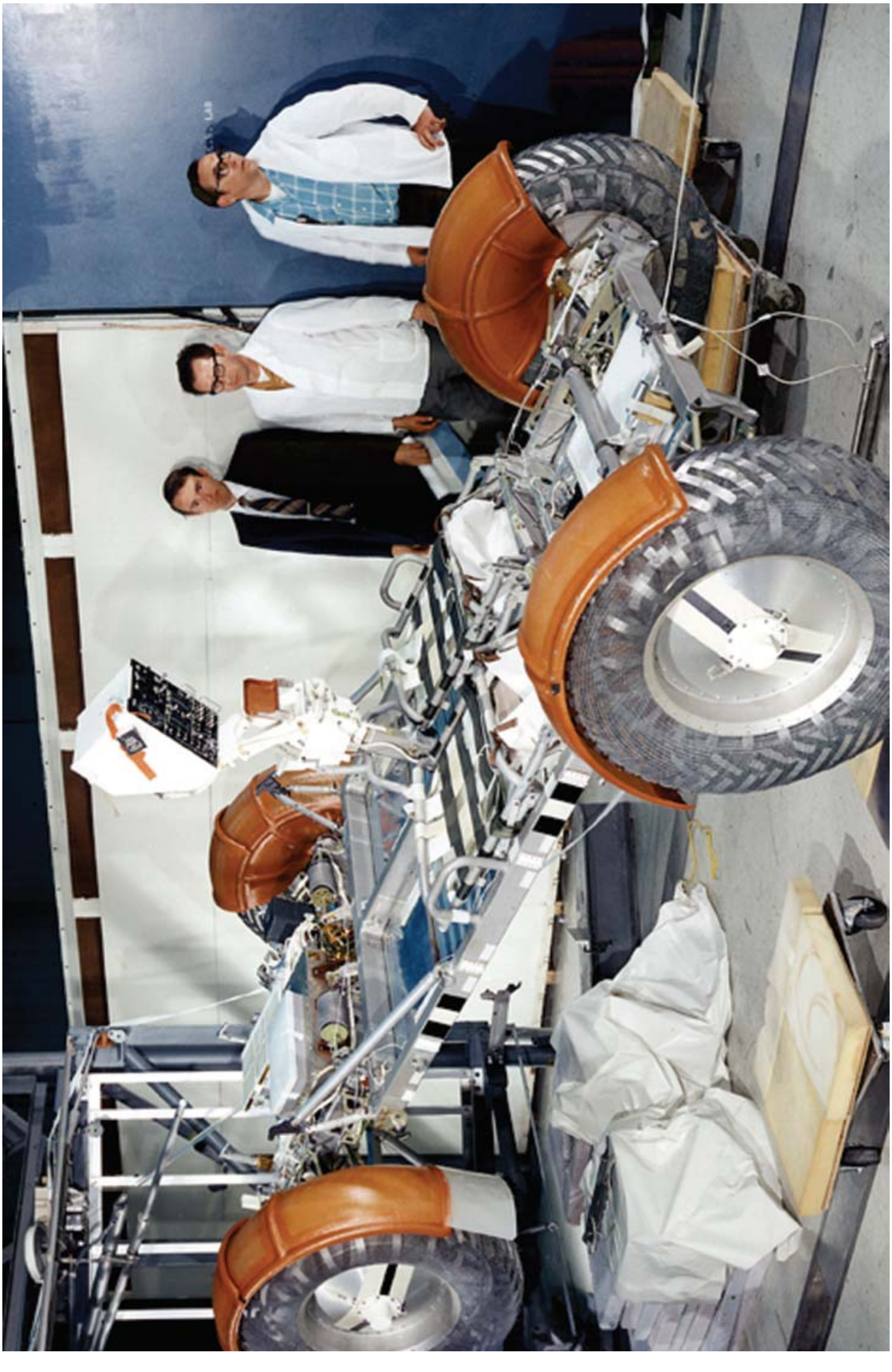
Index







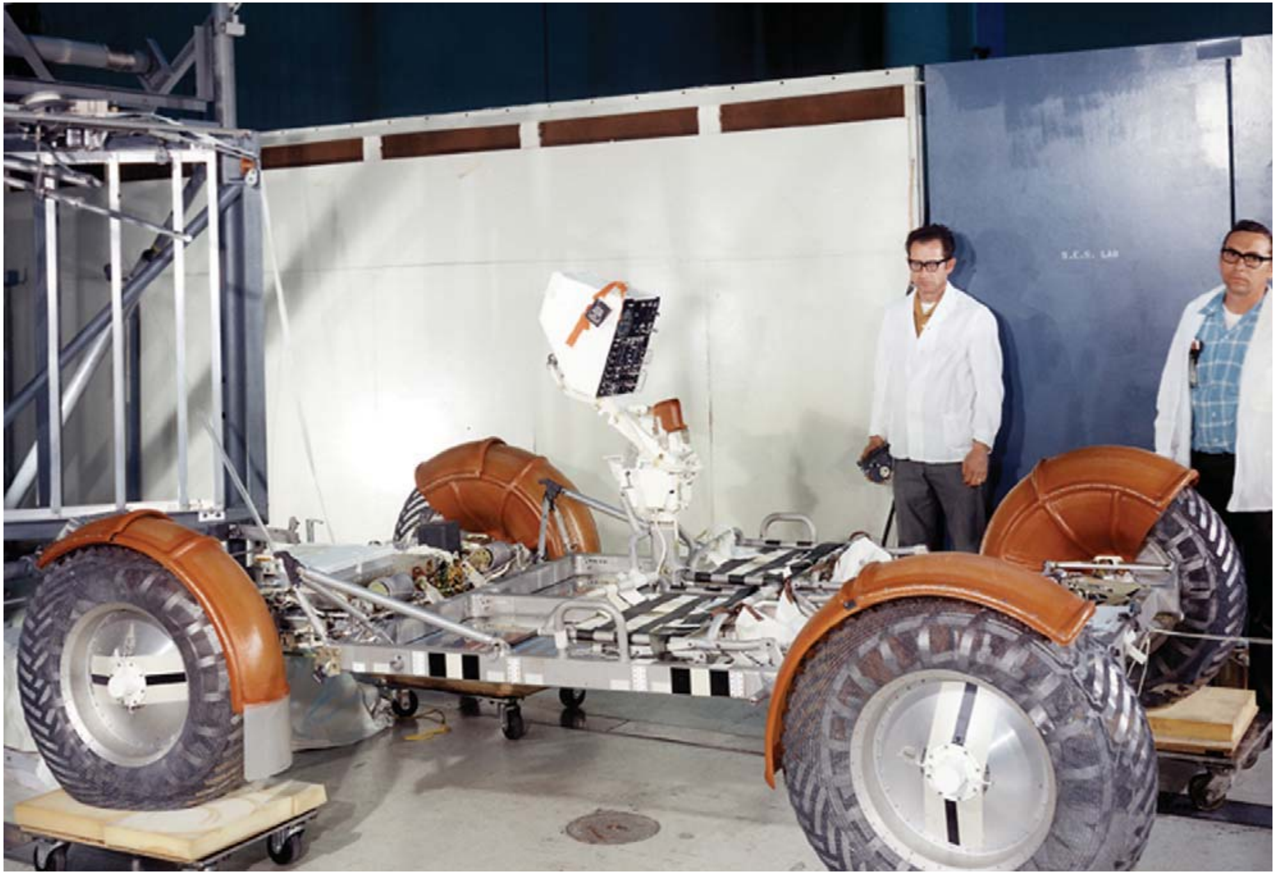


Plate 1–6 Deployment tests of the Lunar Roving Vehicle flight units were conducted at Marshall Space Flight Center (MSFC) in Huntsville, Alabama. (NASA/MSFC)

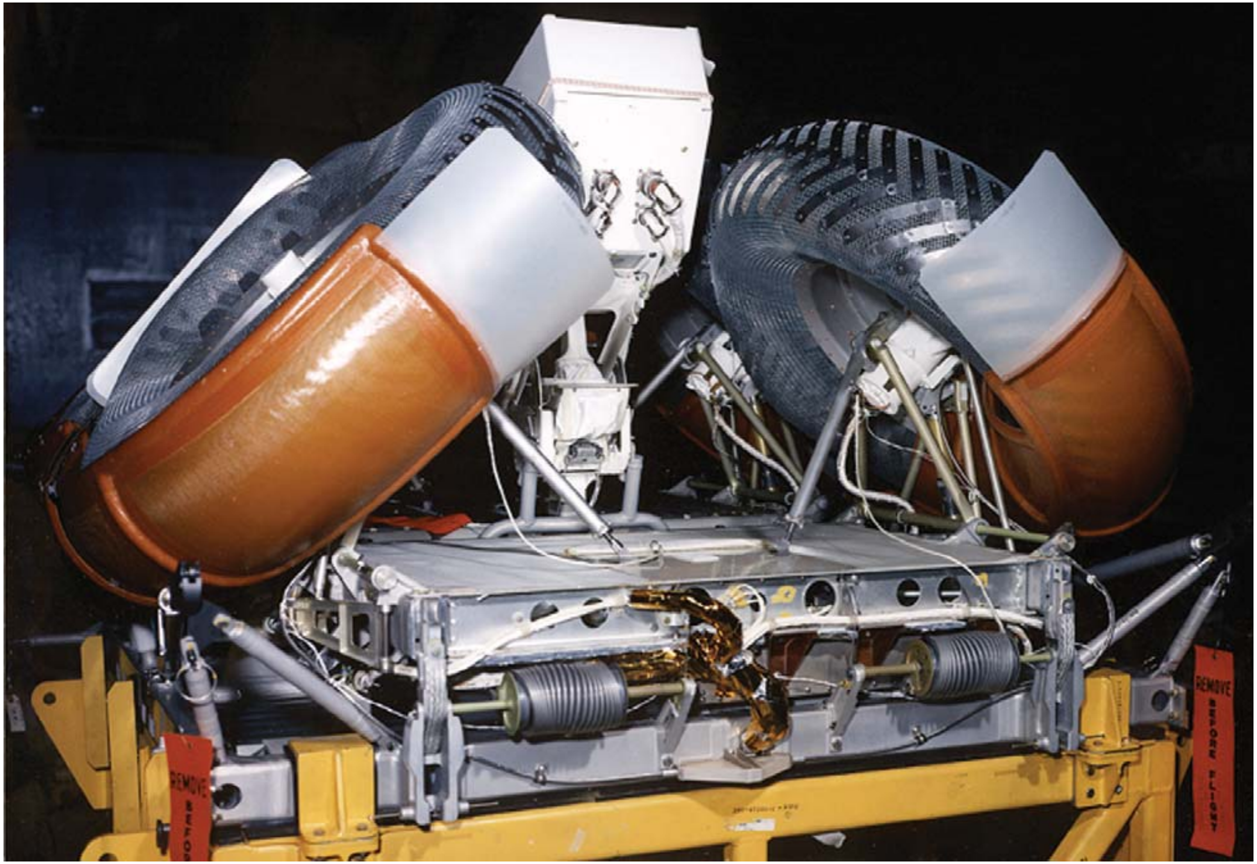


Plate 7 LRV-1 on the Handling and Installation Tool fixture. The LRV was a marvel of mechanical packaging. Note the springs used to deploy the forward chassis. (NASA/MSFC)

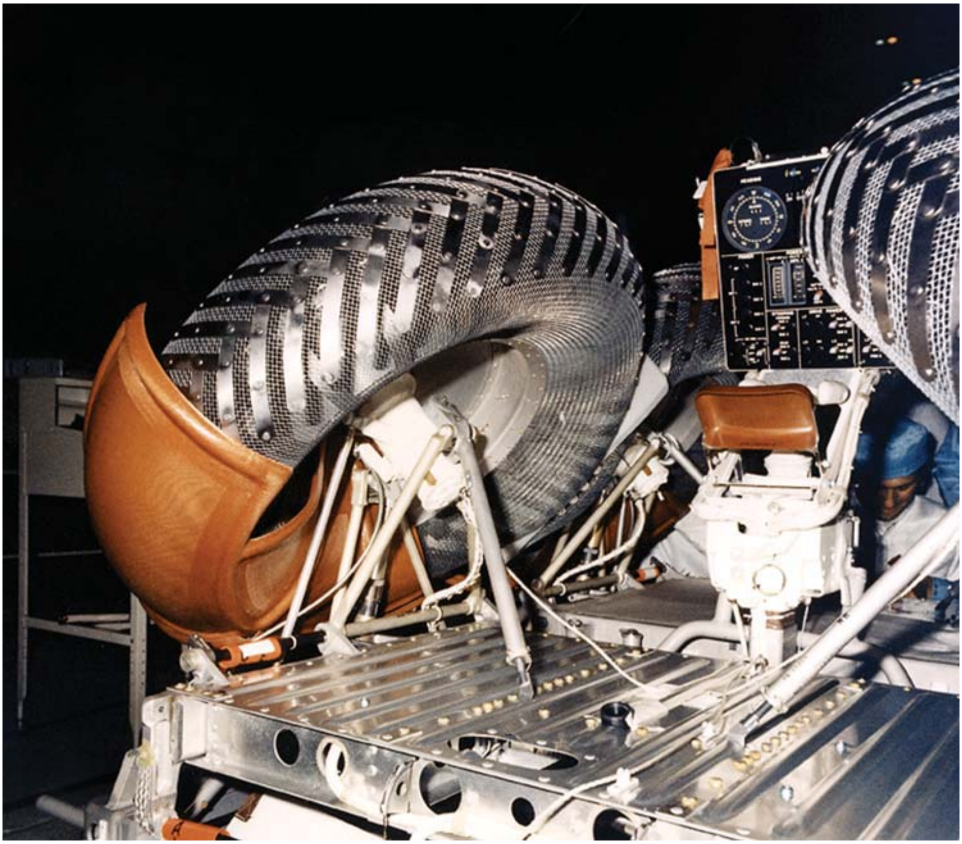


Plate 8 Detail of the folded aft chassis. Note the ribs in the aluminum panels to increase rigidity. (NASA/MSFC)

Plate 9 This photo clearly shows the internal construction of the bump stop to prevent complete collapse of the wire mesh wheel and damage to the rim upon severe impact with large rocks on the lunar surface. (NASA/MSFC)

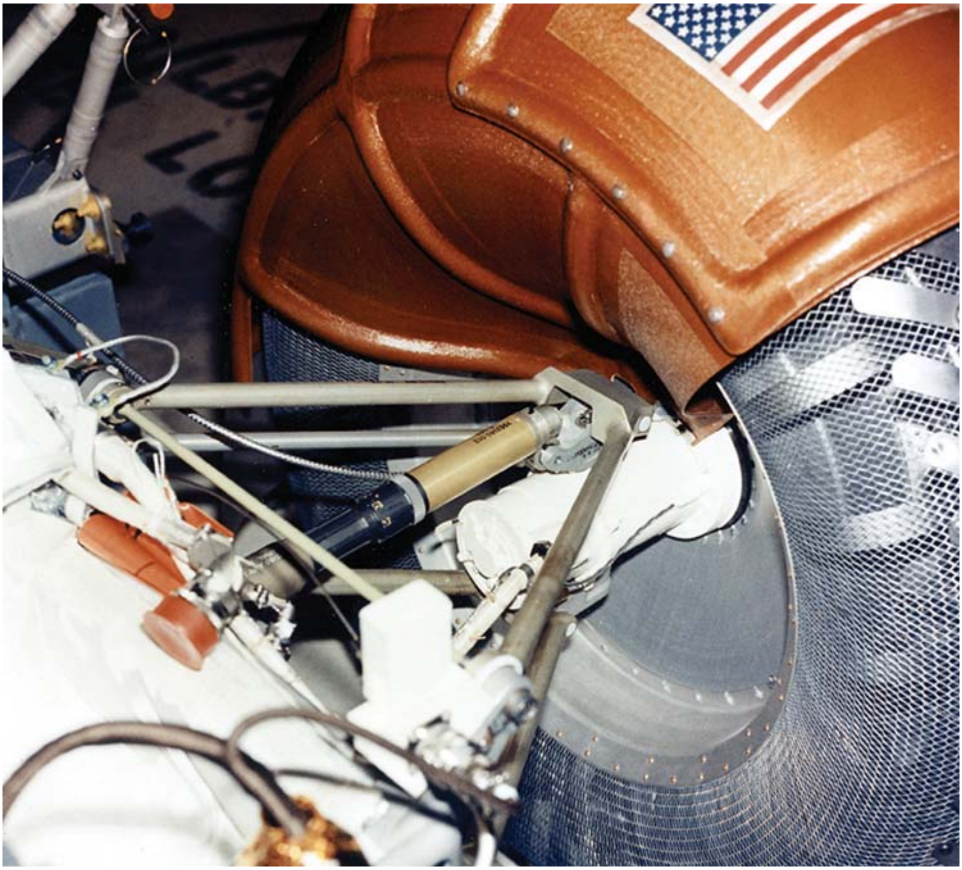


Plate 10 Close-up of the LRV traction drive, suspension control arms and the damper. (NASA/MSFC)

Plate 11 Jim Irwin and Dave Scott take the Geologic Rover (Grover) around the artificial crater field created by the U.S. Geologic Survey at Cinder Lake, near Flagstaff, Arizona in November 1970. (NASA)

Plate 12 Caltech geologist Lee Silver points out a geologic formation at Rio Grande Gorge, New Mexico to the prime and backup crews for Apollo 16. John Young is on the right. Above them in the daytime sky is the target of John Young and Charlie Duke's mission. (NASA)

Plate 13 Charlie Duke and John Young are shown training with the LRV 1-G Trainer at Kennedy Space Center during January 1972. Duke is carrying the Self-Recording Penetrometer to be used for lunar soil mechanics data. (NASA/KSC)

Plate 14 John Young drives the 1-G trainer during EVA training at KSC. The Commander's EVA suit has red stripes on the arms, legs and helmet for positive identification in photographs and during TV transmissions. (NASA/KSC)

Plate 15 The 1-G Trainer is completely reflected in the gold visor of Charlie Duke's helmet during training at Kennedy Space Center. Good view of the 16mm film Data Acquisition Camera. Note the lunar drill core stems. (NASA/KSC)

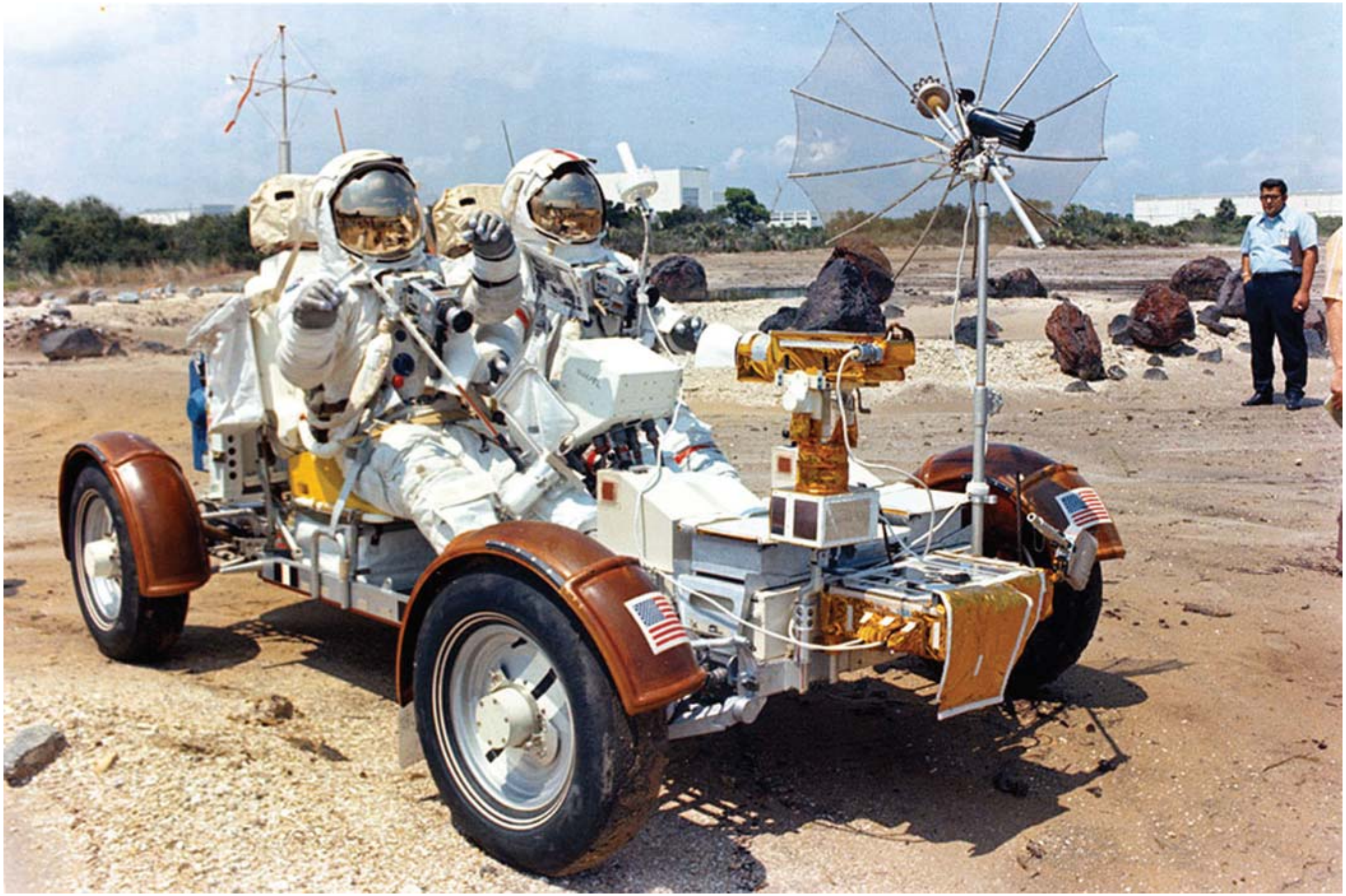


Plate 16 Apollo 17 Commander Eugene Cernan and Lunar Module Pilot Harrison Schmitt trained extensively at KSC with the 1-G Trainer. Schmitt has the LRV Sampler, a new tool he will use for collecting lunar samples from his seat on the LRV. (NASA/KSC)

Plate 17 Apollo 17 backup Commander John Young communicates with Eugene Cernan on the 1-G Trainer during indoor training at KSC in August 1972. Harrison Schmitt is examining the LRV sampler. Ease of use of lunar tools with the EVA gloves was vital in training. (NASA/KSC)

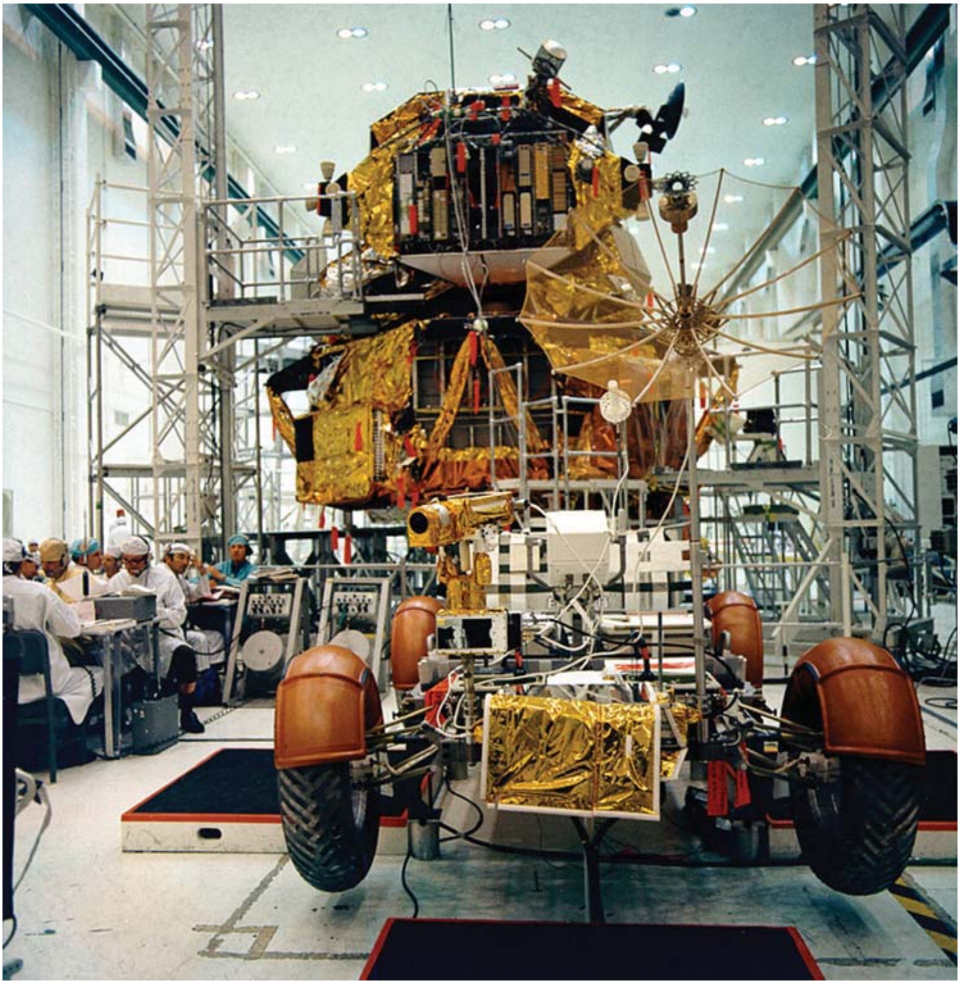


Plate 18 LRV-1 undergoes testing with the Lunar Module *Falcon* in the Operations and Checkout Building at KSC. Specific tests were run to ensure that electrical components did not cause interference during communication between the LRV and the Lunar Module. (NASA/KSC)

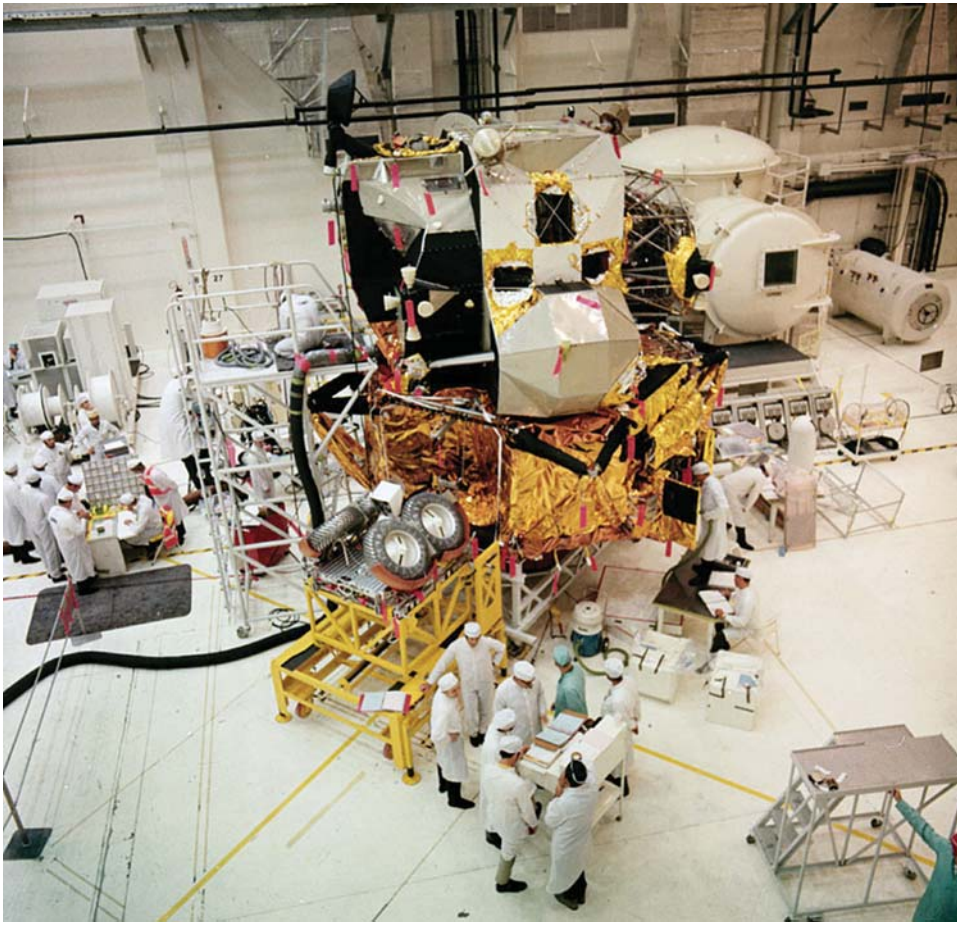


Plate 19 LRV-1 undergoing fit checks with the Lunar Module *Falcon*. Lunar Module Pilot Jim Irwin is standing closest to the LRV with his hand on the Handling and Installation Tool fixture. (NASA/KSC)

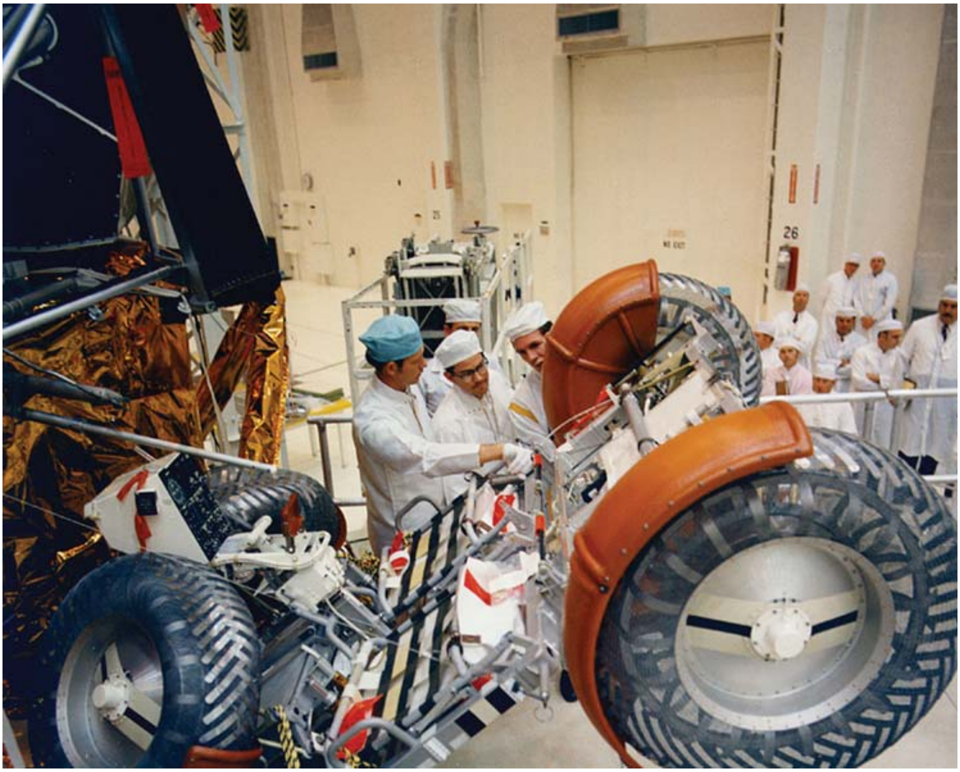


Plate 20 Apollo 15 Commander David Scott (on right) observes a deployment test of LRV-1 from the Lunar Module *Falcon*. Note the LRV's deformed wheels as a result of stowage. The wheels achieved their proper configuration in a short period of time. (NASA/KSC)

Plate 21 LRV-1 is pictured stowed aboard the Lunar Module *Falcon*. It would later receive its own protective thermal blanket. (NASA/KSC)

Plate 22 On a special press day in May 1971 for Apollo 15, David Scott and Jim Irwin took the 1-G Trainer out to explain the LRV's equipment and many features and to answer questions about the use of the LRV on their mission to Hadley-Apennine. (NASA/KSC)

Plate 23 The crew of Apollo 15 included mission Commander David Scott, Command Module Pilot Al Worden, and Lunar Module Pilot James Irwin. (NASA)

Plate 24 Apollo 15 was launched on 26 July 1971. Just after liftoff the four outboard F-1 engines of the Saturn V were gimbaled to point the launch vehicle several degrees away from the Launch Umbilical Tower until it cleared the tower. (NASA)

Plate 25 Watching the launch of Apollo 15 are (from left) Lt. Gen. Samuel Phillips, former Apollo Program Director; Dr. Wernher von Braun; NASA Administrator James C. Fletcher, and NASA Deputy Administrator George M. Low who was previously the Apollo Spacecraft Program Manager. (NASA)

Plate 26 Jim Irwin works at the back the LRV at the end of EVA-1 in this photo taken by David Scott. The chevron pattern from the wheels are clearly evident in the lunar soil. The LRV's left front fender extension is missing, probably lost during a traverse. (NASA)

Plate 27 After deploying the American flag, David Scott photographed Jim Irwin offering his salute, in one of the most famous pictures of the Apollo era. Hadley Delta towers in the distance. (NASA)

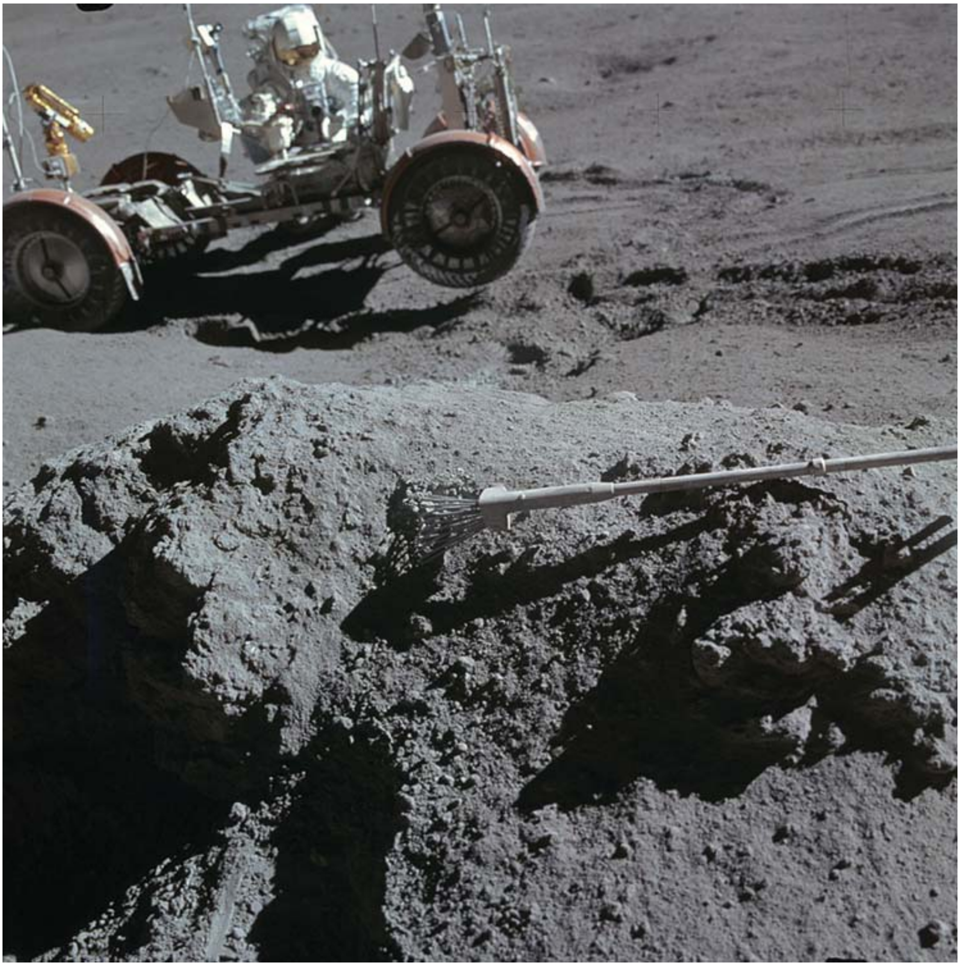


Plate 28 During the Station 6A stop, David Scott placed the sampling tongs on top of the boulder to lend scale, and took this photo. The location was so steep, Jim Irwin had to stop the LRV from sliding, with the left rear wheel actually off the surface. (NASA)

Plate 29 Jim Irwin took this photo of the Lunar Module *Falcon* with one landing leg in a shallow depression during EVA-2. In the distance, David Scott is walking away from the LRV toward the Central Station. (NASA)

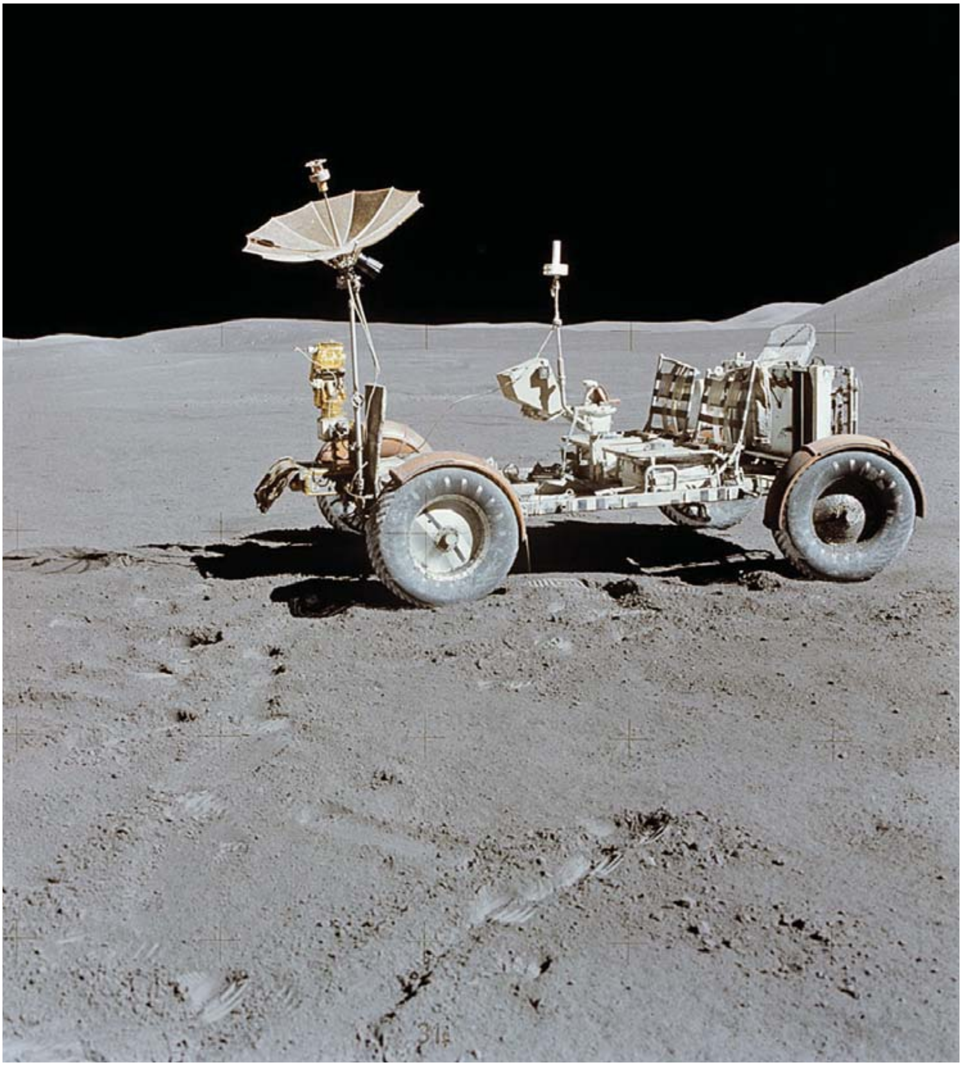


Plate 30 At the end of EVA-3, David Scott drove the LRV out to the VIP site, so named as the best position for the TV camera to record the liftoff *Falcon's* ascent stage. Behind the LRV, Scott placed a small figure and the plaque listing fallen astronauts and cosmonauts, and then placed a small red-covered Bible against the hand controller. (NASA)

Plate 31 The crew of Apollo 15 is greeted aboard the recovery ship *U.S.S. Okinawa* on 7 August 1971 by a jubilant Robert R. Gilruth, first Director of the Manned Spacecraft Center, later the Johnson Spacecraft Center. (NASA)

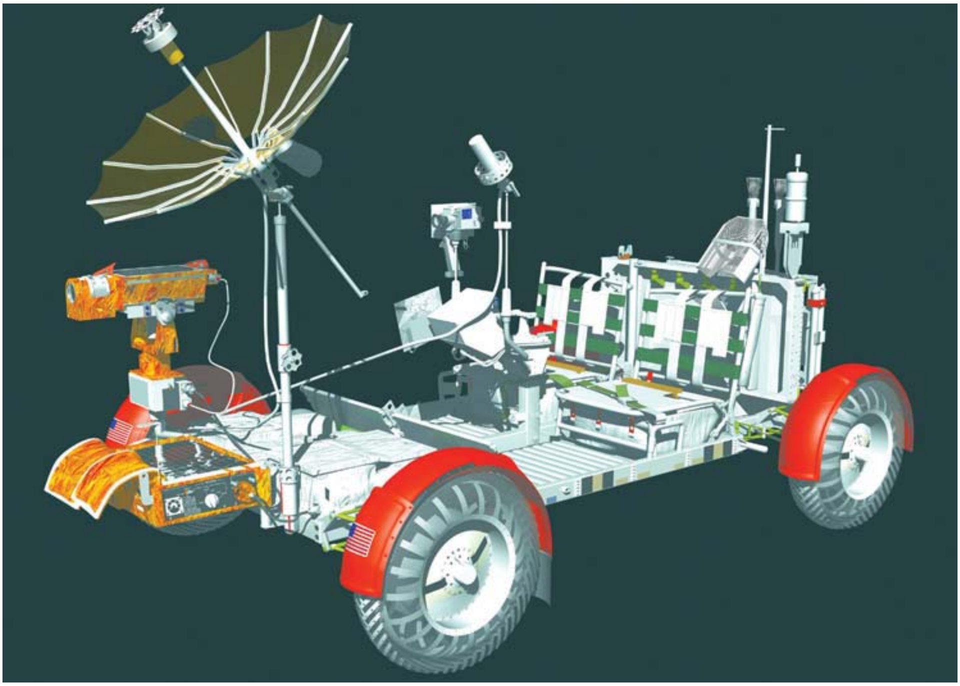


Plate 32 The first detailed 3D computer model of the Lunar Roving Vehicle was created by Don McMillan, who also used special software to create the first animated deployment sequence of the LRV from the Lunar Module. Working from photographs of the LRV flight units, McMillan modeled each part using LightWave 3D software to create the final assembled 3D model and animations, more than 30 years after Apollo 17. See the Appendix for information on these creations. (Don McMillan)

Plate 33 The crew of Apollo 16 included Commander John Young (center), Command Module Pilot Ken Mattingly (left) and Lunar Module Pilot Charlie Duke. (NASA/MSFC)

Plate 34 SA-511, on the Mobile Launch Platform, is moved to launch complex LC-39A by the crawler transporter on 13 December 1971. Problems with the Command Module Reaction Control System required the Saturn's return to the VAB. It would finally launch on 16 April 1972. (NASA)

Plate 35 This curved plaque was fastened to a leg of the Lunar Module *Orion* descent stage. One day it will be read by a future generation of lunar explorers who return to the Descartes Highlands. (NASA)

Plate 36 Charlie Duke took this photo of the LM and LRV at the start of EVA-2. Note the lunar dust on the right rear fender of the LRV. John Young collects a sample behind the rover. Dust was a pervasive problem on the Moon and the LRV had to routinely be brushed clean of the dark, abrasive lunar soil. (NASA)

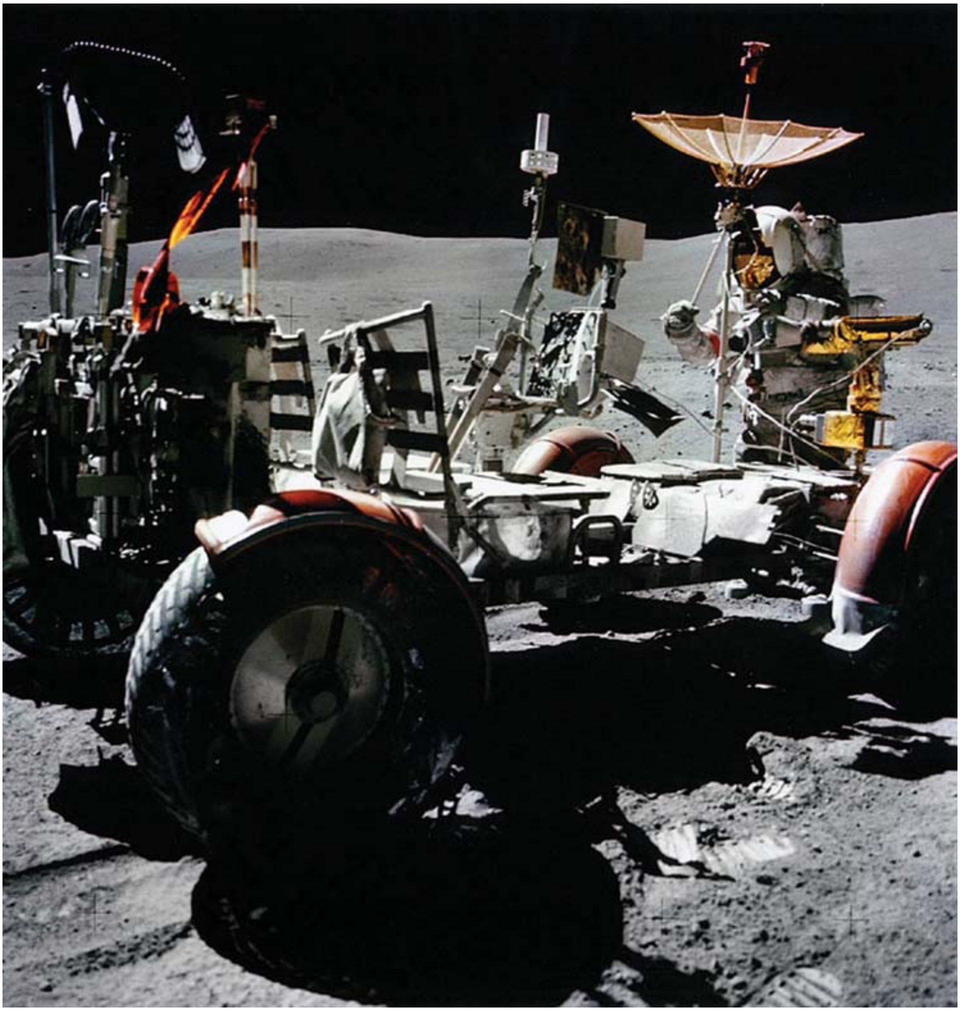


Plate 37 To ensure proper alignment of the high-gain antenna, the mission commander looked through a small window of the alignment scope until the Earth was visible. He then locked the antenna in position with the antenna boom, as Young is doing in this picture. The right rear fender extension was torn from its extension rails at Station 8 during EVA-2. No attempt was made to repair it. (NASA)

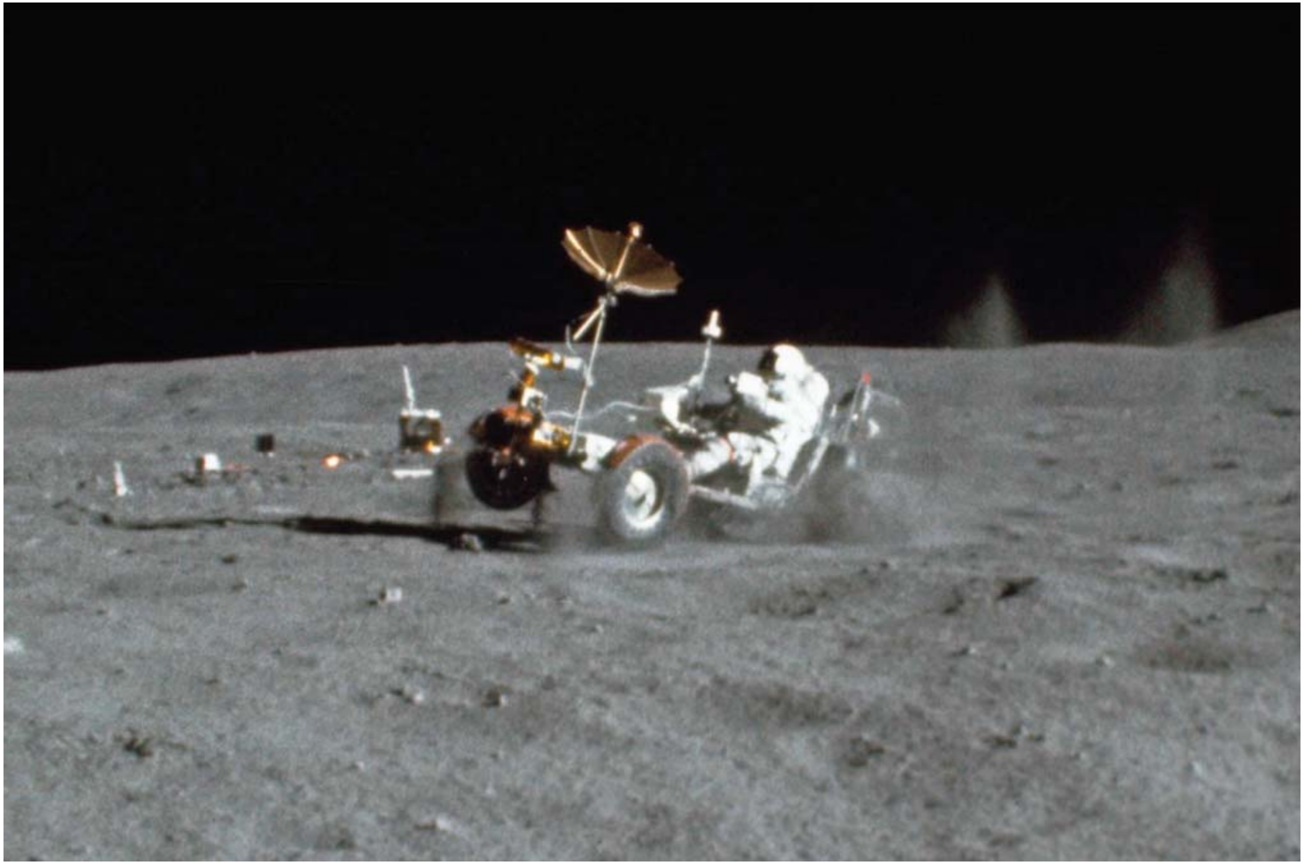


Plate 38 The Grand Prix was a test of the LRV under hard acceleration, turning and braking, recorded by Charlie Duke with the 16mm Data Acquisition Camera, from which this still was taken. John Young has both front wheels off the lunar surface while sending rooster tails of lunar soil from the LRV's wheels. (NASA/ALSJ)

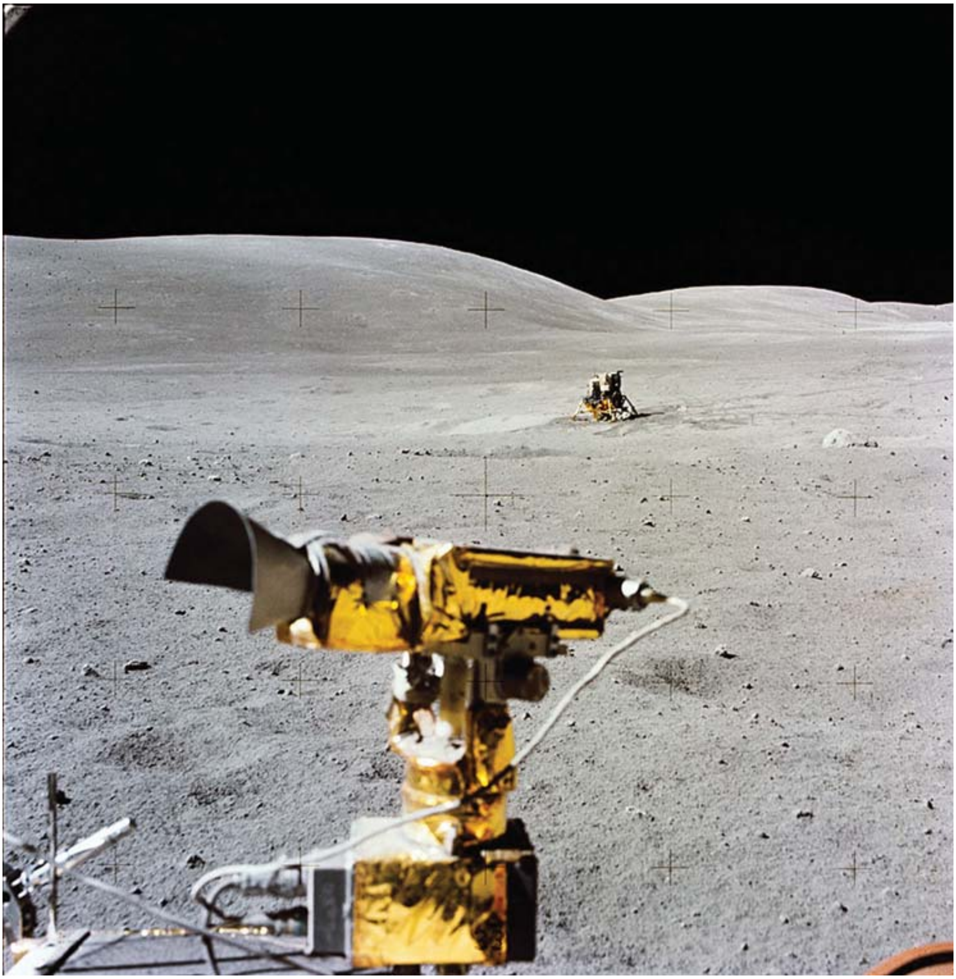


Plate 39 An excellent view of the Descartes Highlands taken by Charlie Duke from the LRV during EVA-3. The TV camera featured a new Sun shade used for the first time on Apollo 16, which dramatically reduced glare on the lens. (NASA)

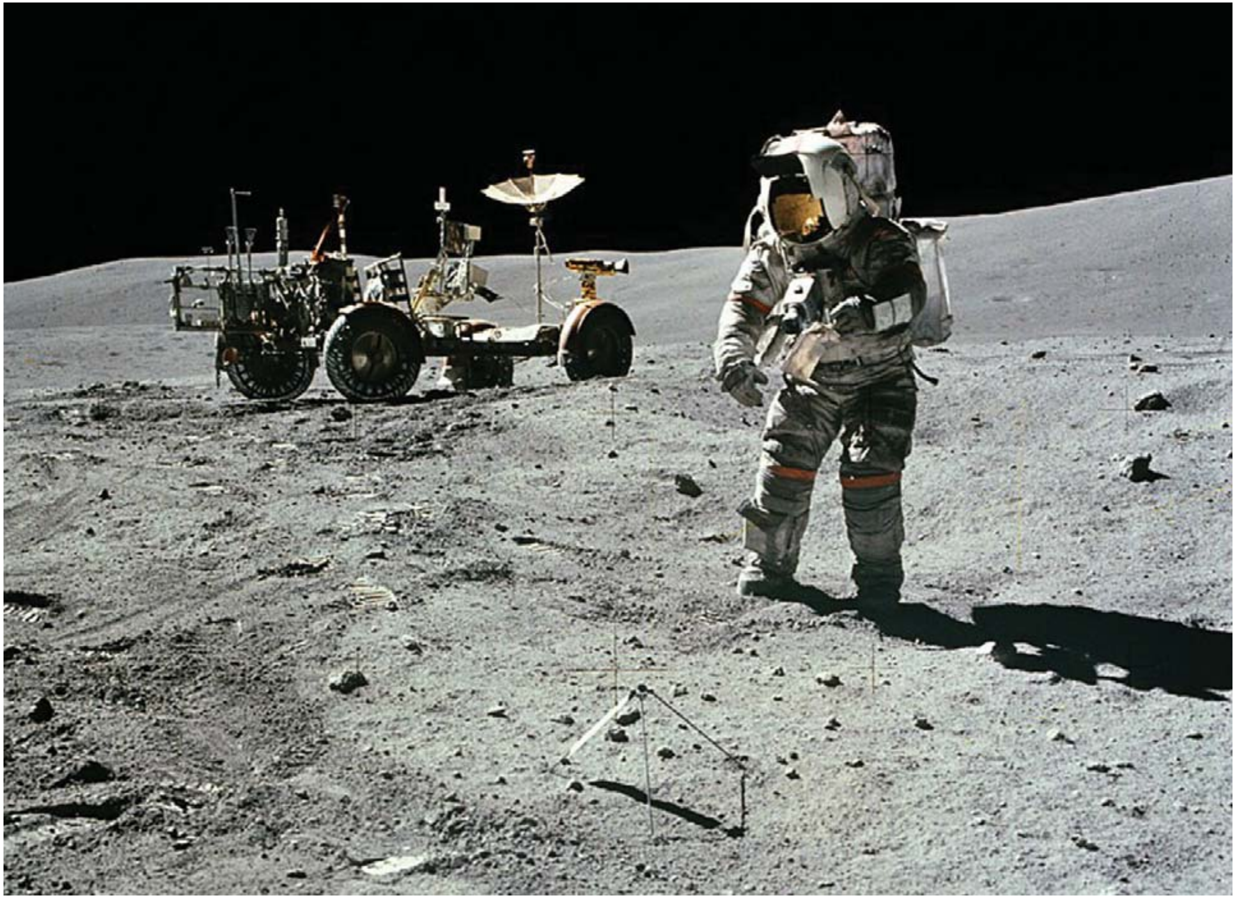


Plate 40 Charlie Duke photographed John Young as he took a sample at the Station 10 stop. Young remarked that driving conditions as a result of Sun angle and direction of the traverse made it nearly impossible to detect surface hazards in front of the LRV. (NASA)

Plate 41 As a result of the lost right rear fender extension which was not repaired, Charlie Duke's EVA suit was covered with lunar dust, as was much of the forward part of the LRV by the end of EVA-3 when John Young took this photo. The battery covers were opened as scheduled for cooling. (NASA)

Plate 42 The crew of Apollo 17 poses with the 1-G Trainer and the awesome Saturn V that will take them to the Moon. Mission Commander Eugene Cernan sits on the trainer. Standing behind him are Lunar Module Pilot Harrison Schmitt (left) and Command Module Pilot Ronald Evans. (NASA)

Plate 43 After deploying LRV-3 at the Taurus-Littrow landing site, Capt. Cernan took the vehicle for a test drive and was pleased to learn that both front and rear steering were operating perfectly. Together with Harrison Schmitt, he would outfit the LRV before their first traverse. (NASA)

Plate 44 Harrison Schmitt works at the LRV toward the end of EVA-3. The Surface Electrical Properties pallet is resting against the landing leg of the Lunar Module *Challenger*. (NASA)

Plate 45 The pressurized EVA suit made it difficult to bend at the waist while trying to get into the LRV, as shown here with Harrison Schmitt at the Station 9 stop. He is holding the LRV Sampler in his right hand. Good photo showing the radiating surfaces of the TV camera and the Lunar Communications Relay Unit (LCRU). (NASA)

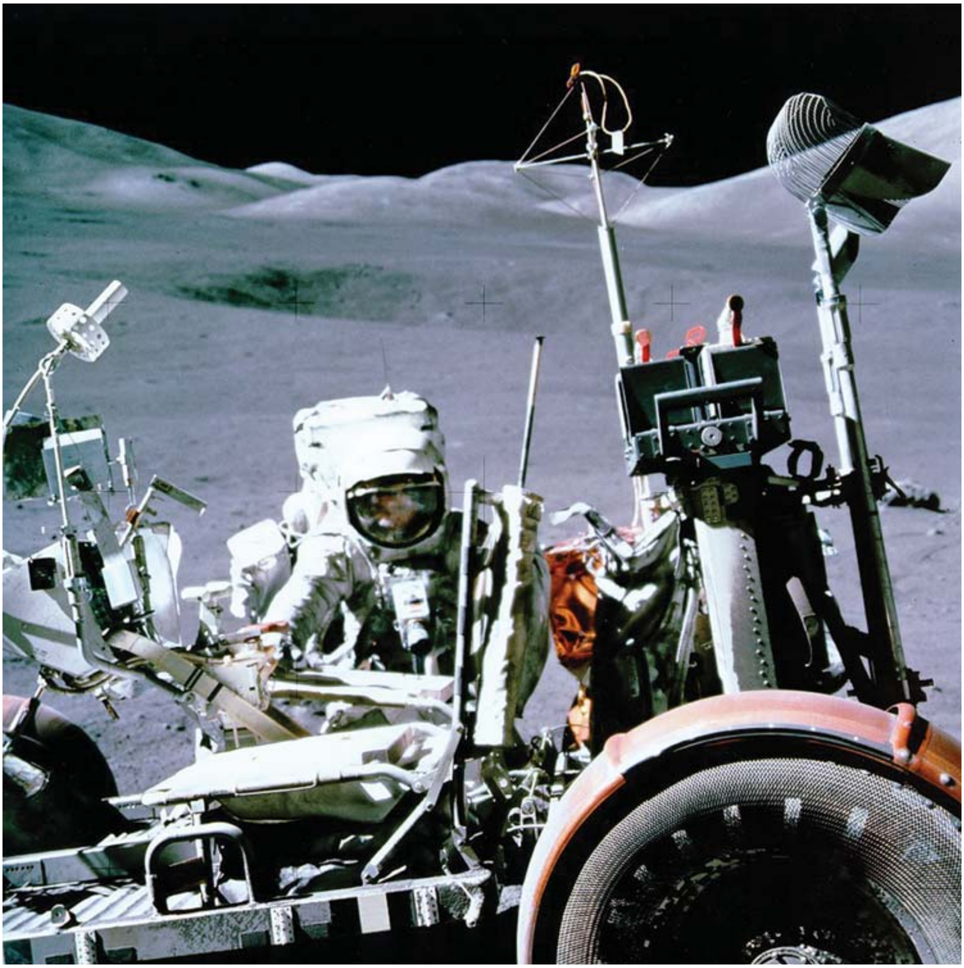


Plate 46 Harrison Schmitt works beside the LRV at Station 6. This is one of the few photographs taken of an Apollo astronaut with his gold visor up. The Surface Electrical Properties antenna was mounted behind Schmitt's seat. (NASA)

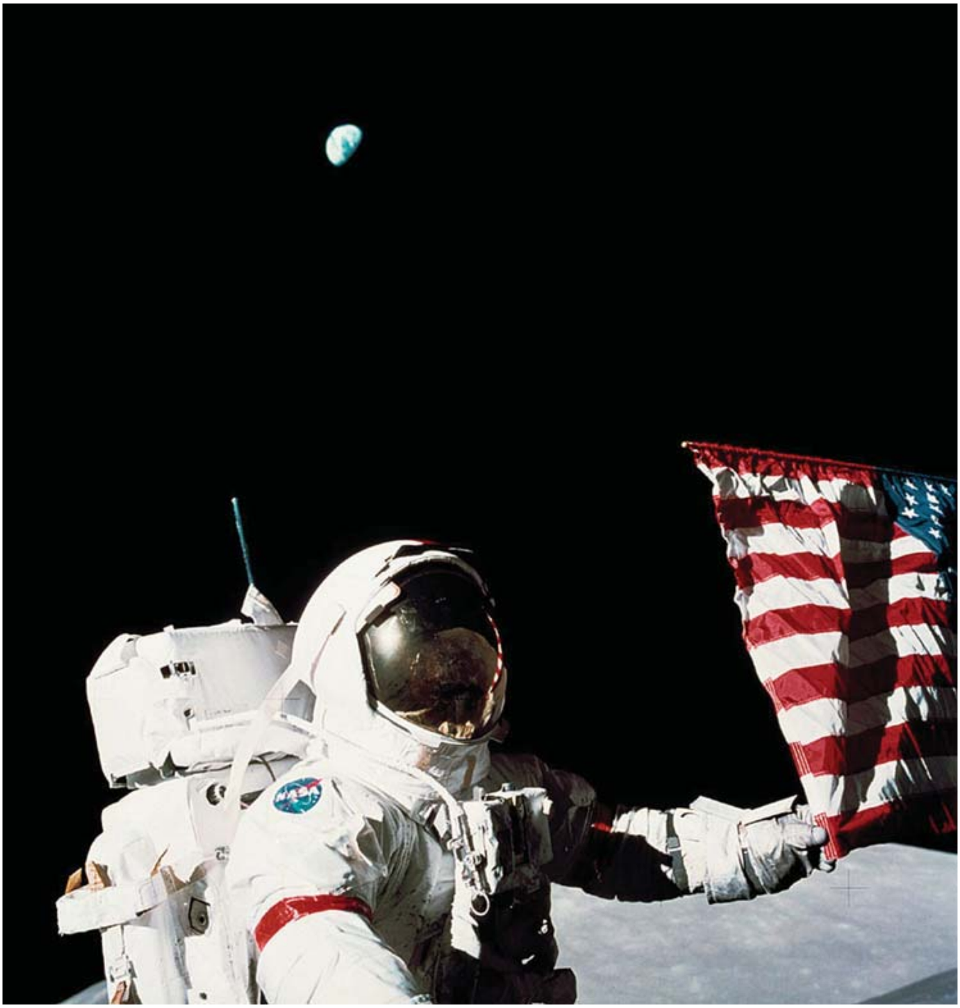


Plate 47 In this striking photograph, Capt. Eugene Cernan poses holding the United States flag, with the Earth behind him. (NASA)

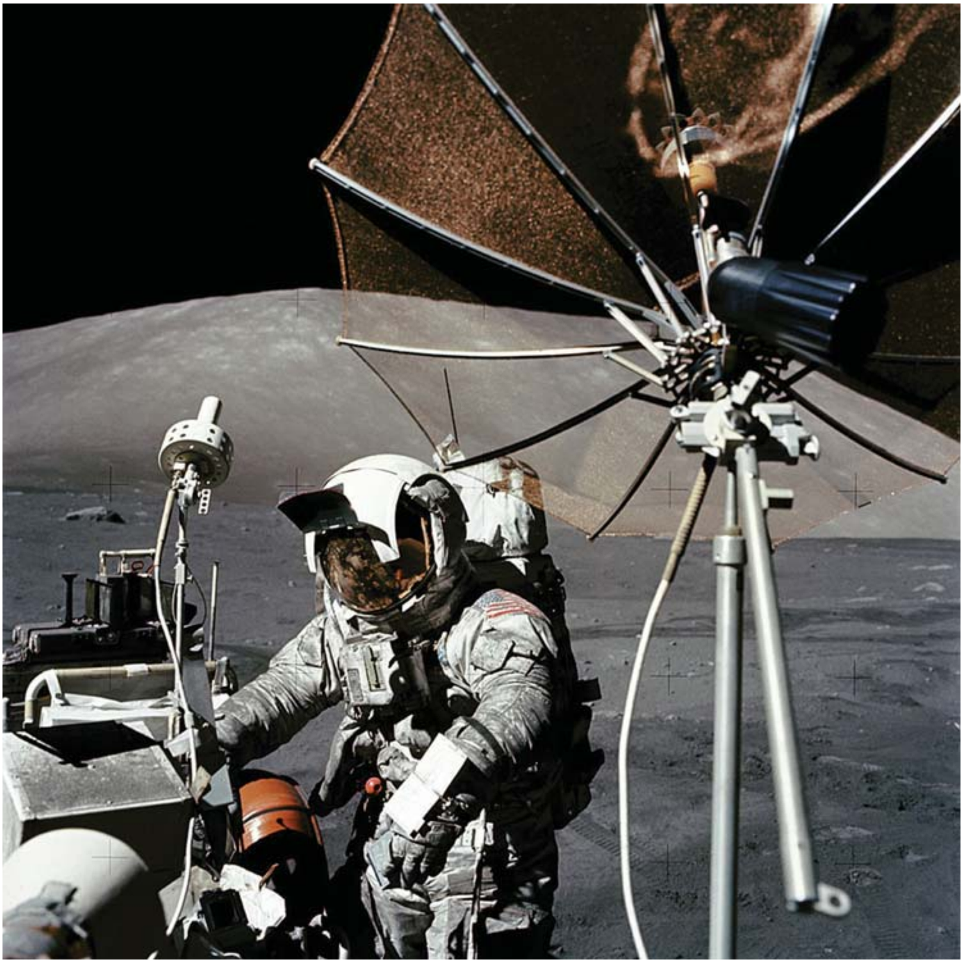


Plate 48 Cernan took this photo of Harrison Schmitt on the Commander's side of the LRV at the end of EVA-3. The reflection on the gold mesh of the high-gain antenna is from the radiating mirrors on top of the TV camera, not visible in this photo. Note the lunar dust on top of the Display and Control Console. (NASA)

Plate 49 2002 marked the dedication of the new Eugene Shoemaker Center for Astrogeology in Flagstaff, Arizona. Among the attendees were three of the most influential geologists involved in the Apollo J-Missions: Dr. William Muehlberger (with glasses), Dr. Gordon Swann (standing) and Dr. Lee Silver. (U.S. Geologic Survey)

Plate 50 Also attending the Shoemaker Center for Astrogeology dedication were (from left) Dr. Gerald "Jerry" Schaber, Don Beattie, Rutledge "Putty" Mills, and perhaps the USGS' most illustrious member, Dr. Harrison "Jack" Schmitt, Lunar Module Pilot on Apollo 17. (U.S. Geologic Survey)

Plate 51 Technicians at the Kennedy Space Center close the solar panels on MER-2 in preparation for mounting in the lander. Mars Exploration Rover *Spirit* was launched toward Mars on 10 June 2003, and *Opportunity* followed on 7 July 2003. They landed successfully on 4 and 24 January 2004 (Universal Time). (NASA/KSC)

Plate 52 The Mars Exploration Rovers (MERs) *Spirit* and *Opportunity* have surpassed even the most optimistic projections regarding their longevity and performance on the hostile surface of Mars. Superb engineering, meticulous manufacturing and assembly, rigorous and through testing, and backup procedures, among other aspects, resulted in rovers that have produced a wealth of scientific data and wondrous images that will be studied for years. (NASA/JPL)

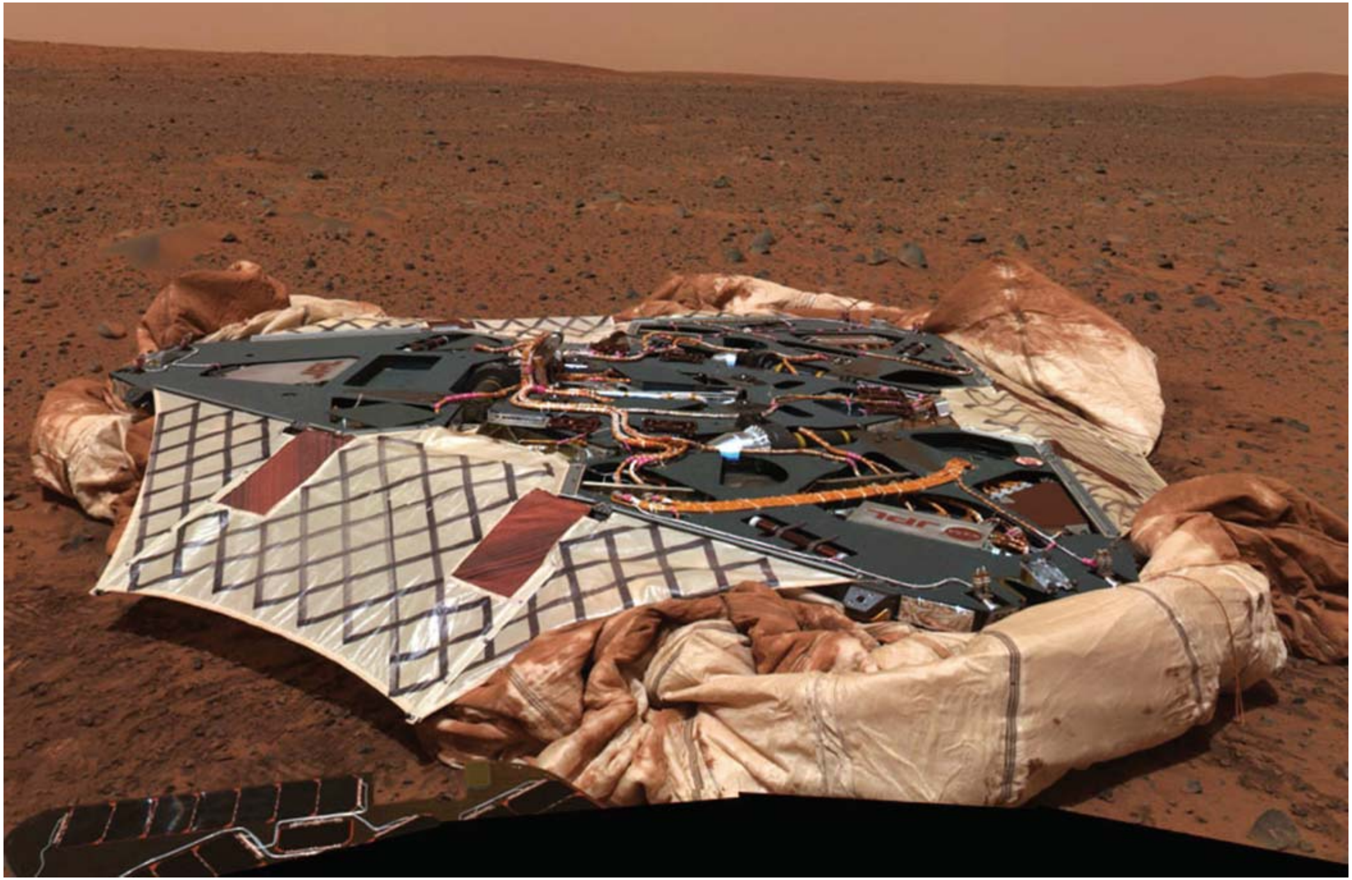


Plate 53 After *Spirit* successfully landed at Gusev Crater, the spacecraft's airbags were deflated and retracted. *Spirit* rolled onto the Martian surface just over ten days after landing. On the sixteenth Martian day, or sol, the MER took this image of its lander. (NASA/JPL)

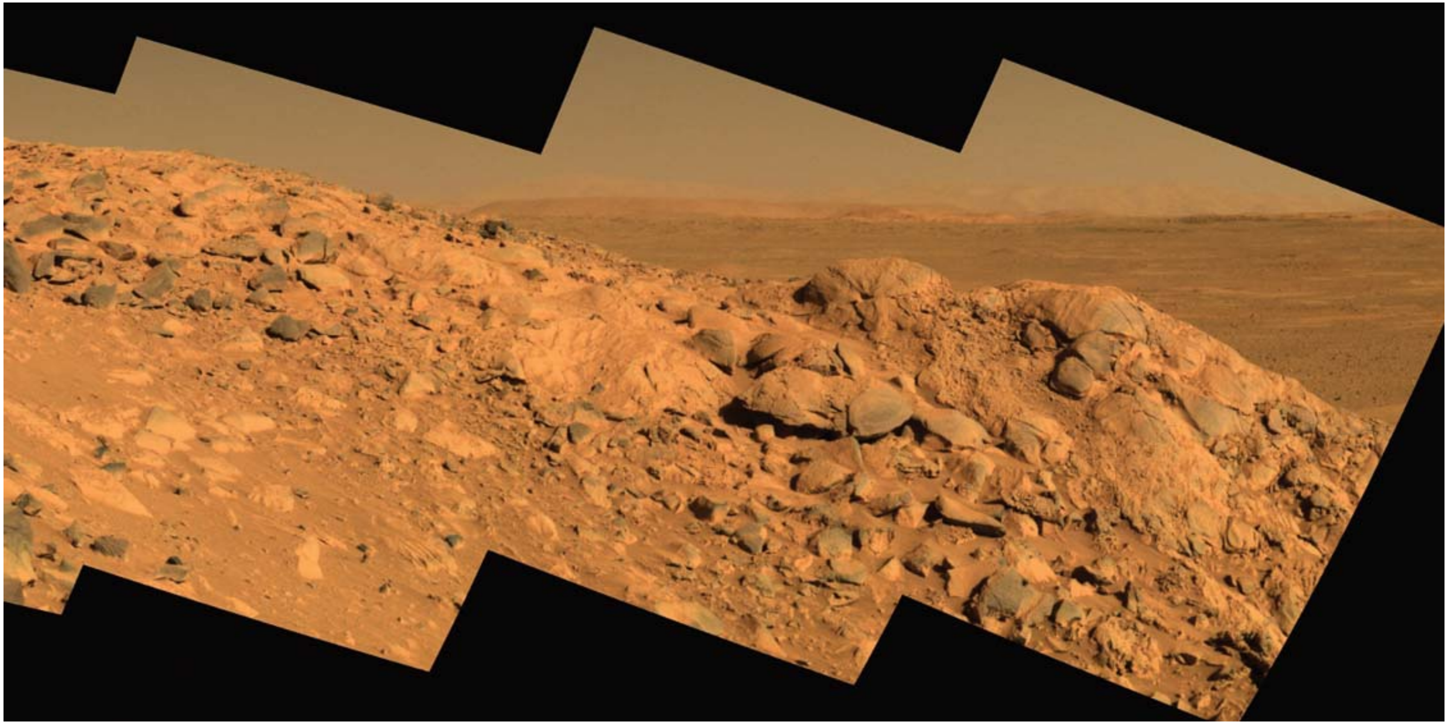


Plate 54 This composite image taken by *Spirit's* panoramic camera on sol 210 (5 August 2004) shows a rock outcrop identified as "Longhorn.". It was taken during its climb of Columbia Hills. In the distance is Gusev Crater and on the horizon an intriguing range of mountains. (NASA/JPL)

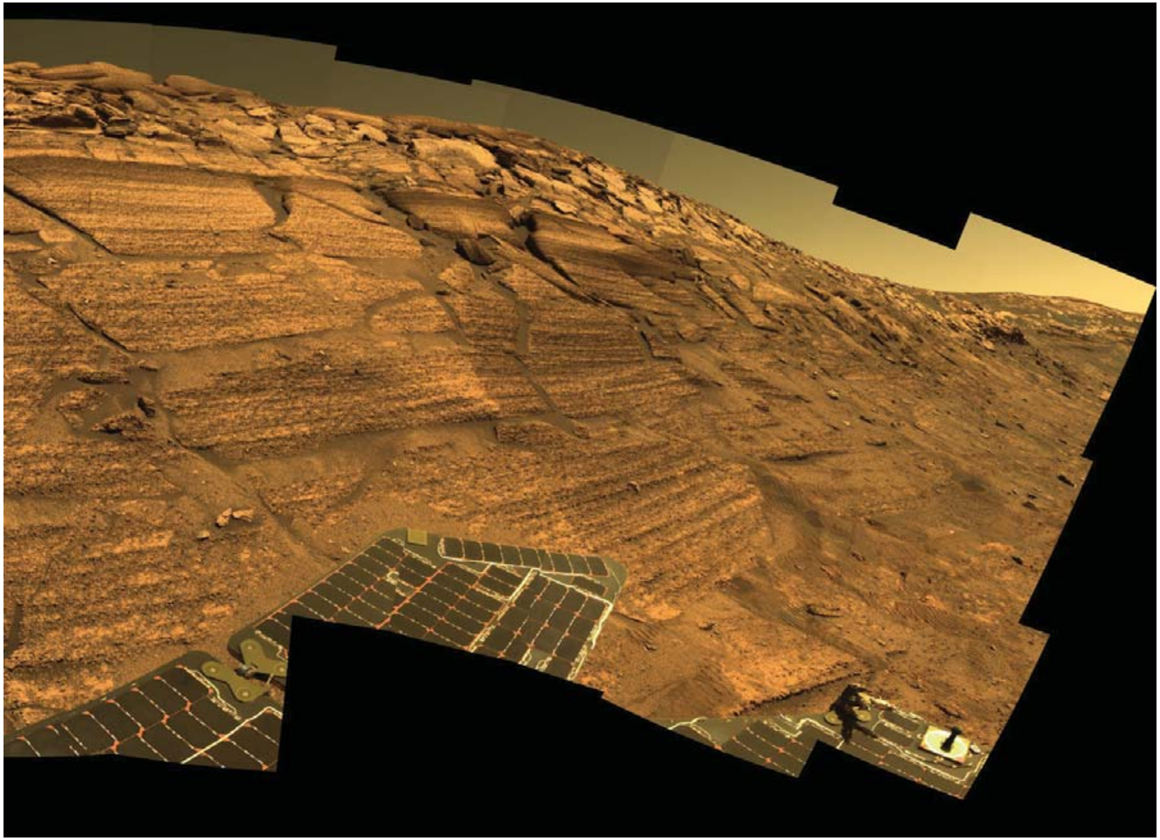


Plate 55 The Mars Exploration Rover *Opportunity* entered ''Endurance Crater'' and revealed compelling evidence of erosion, possibly due to water. The rover climbed the steep walls of the crater to capture this image mosaic of ''Burns Cliff'' during November 2004. (NASA/JPL)

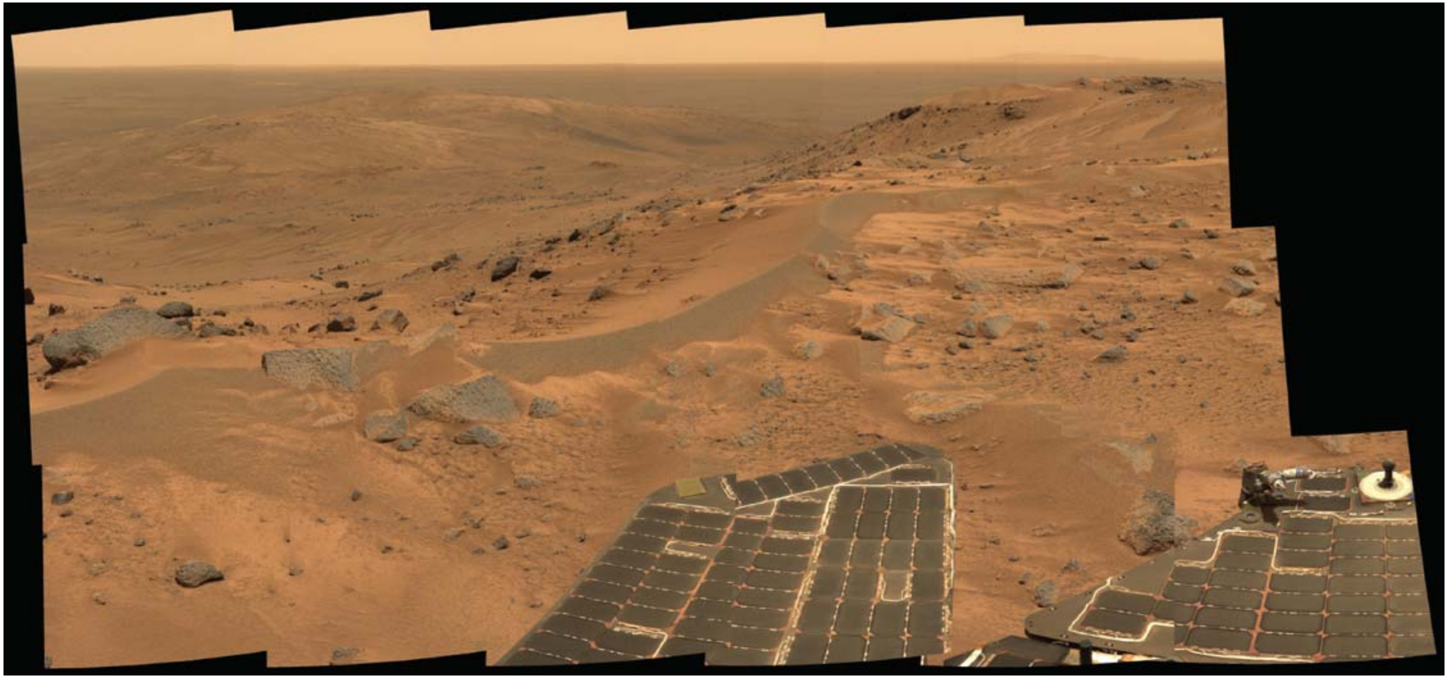


Plate 56 During its assault on the summit of ''Husband Hill'', the rover *Spirit* took this panorama between sols 536 and 543 (6-13 July 2005). To reach this elevation over such rugged terrain took careful, deliberate and methodical planning and driving by the Mars Exploration Rover team. (NASA/JPL)

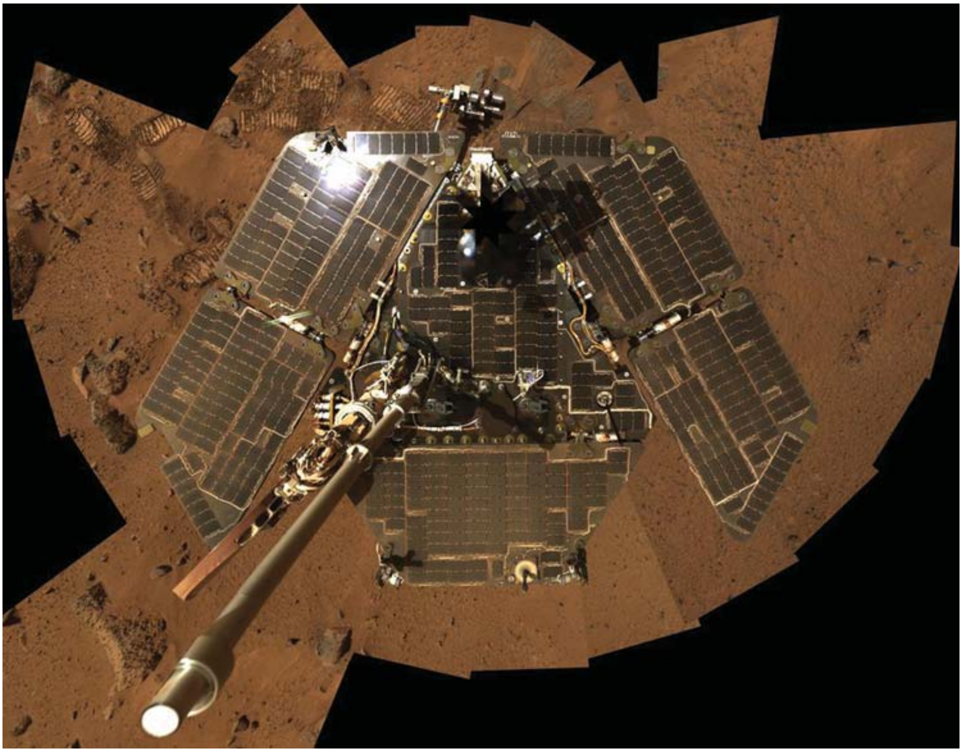


Plate 57 *Spirit* took this self-portrait on sol 585, after spending two years on the surface of Mars. An unexpected bonus of the occasional winds the rovers encountered was the cleaning of accumulated dust from their solar panels, which has permitted the rovers to continue to power their electrical systems. Note the rover's wheel marks in the Martian soil. (NASA/JPL)

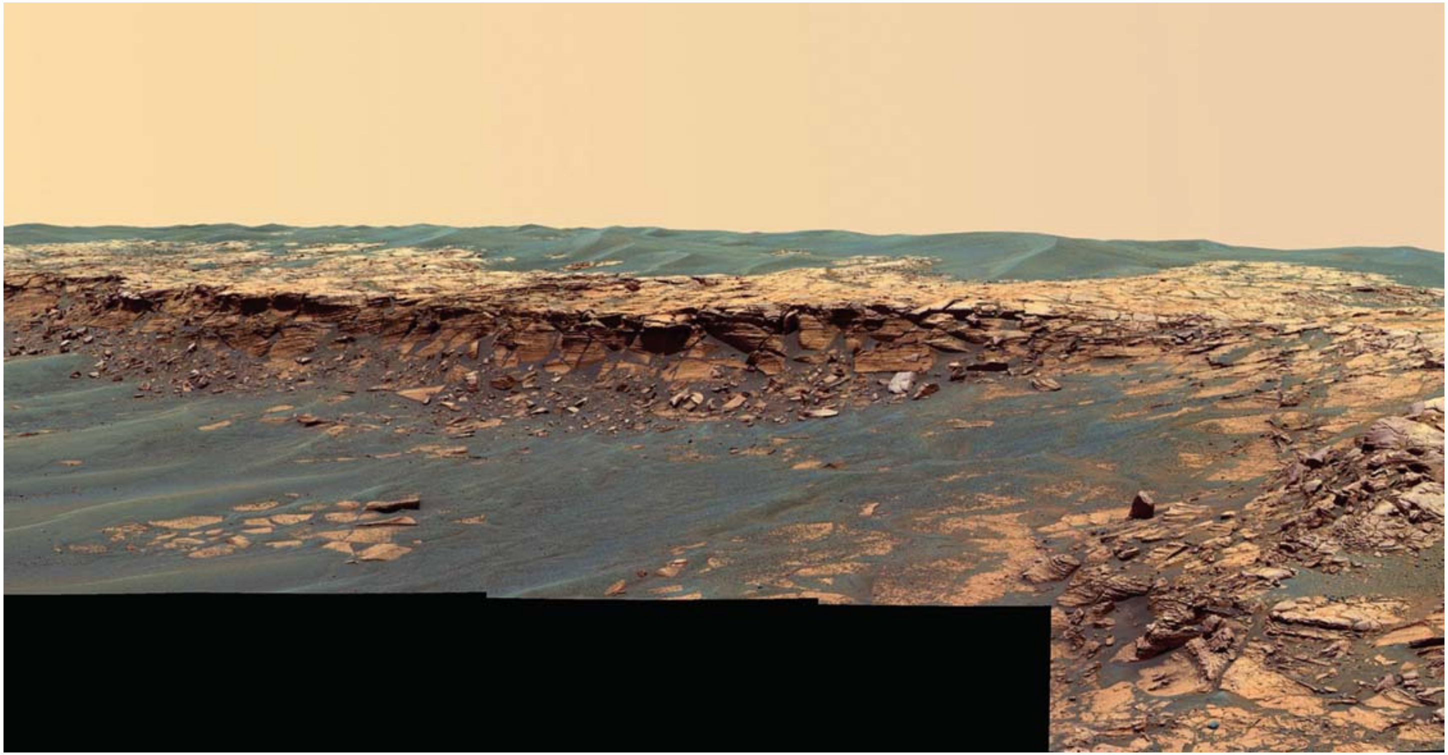


Plate 58 *Opportunity* took this panorama of the ‘‘Payson’’ outcrop on the western edge of Erebus Crater during sol 744 (26 February 2006). The rover has special filters that enhance subtle color differences between the rocks and soil, producing this false-color image. (NASA/JPL-Caltech/USGS/Cornell).

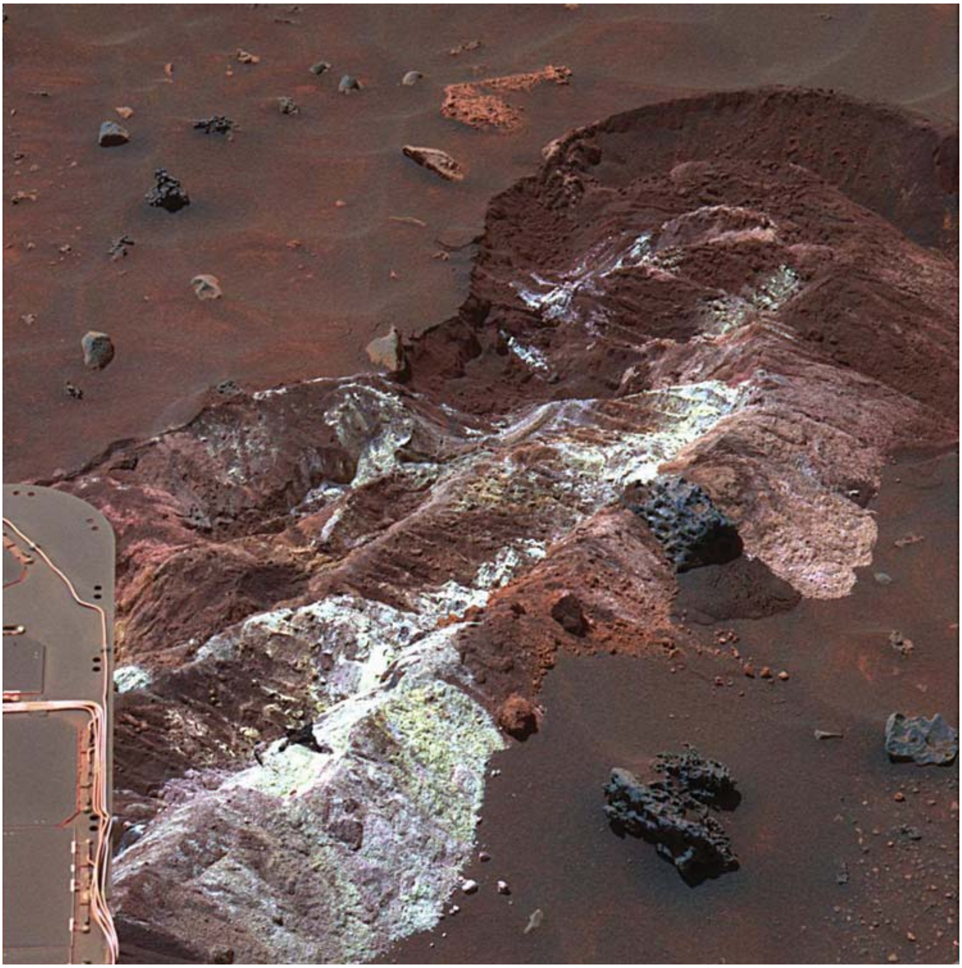


Plate 59 During sol 721, *Sprit* stirred up these very bright deposits while driving toward its next destination, ‘‘Home Plate’’ south of ‘‘Husband Hill.’’ Using the rover’s instruments, scientists determined that the material comprises salts with iron-bearing sulfates, probably deposited by water. (NASA/JPL/Cornell)

Plate 60 The Mars Scientific laboratory will be even larger than the MERs and will have even more capability and longevity. It will be launched in 2009. (NASA/JPL)

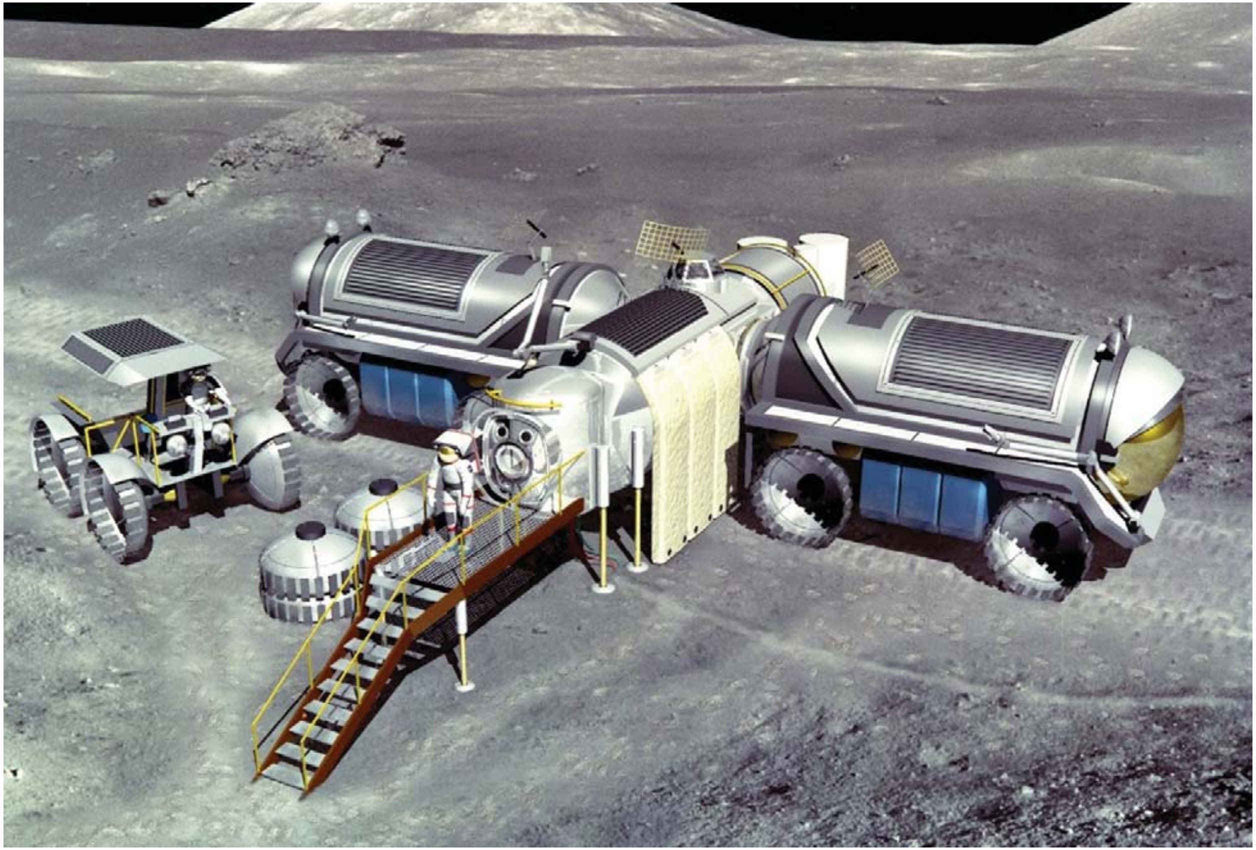


Plate 61 By 1993, the Planetary Projects Office at Johnson Space Center had developed a multi-function lunar facility that employed pressurized rovers, a logistics module and EVA storage and maintenance to provide living and working facilities. The heavy-lift launch vehicles necessary to get this equipment to the Moon did not exist at the time. (NASA/John Frassanito and Assoc.)

Plate 62 SCOUT project lead Frank Delgado discusses test procedures with Joe Kosmo, test lead for the Deserts RATS in Arizona during 2005. Arizona was the site of much testing and training during the Apollo era. The Moon is visible above them in the daytime sky. (NASA/JSC/GRC)

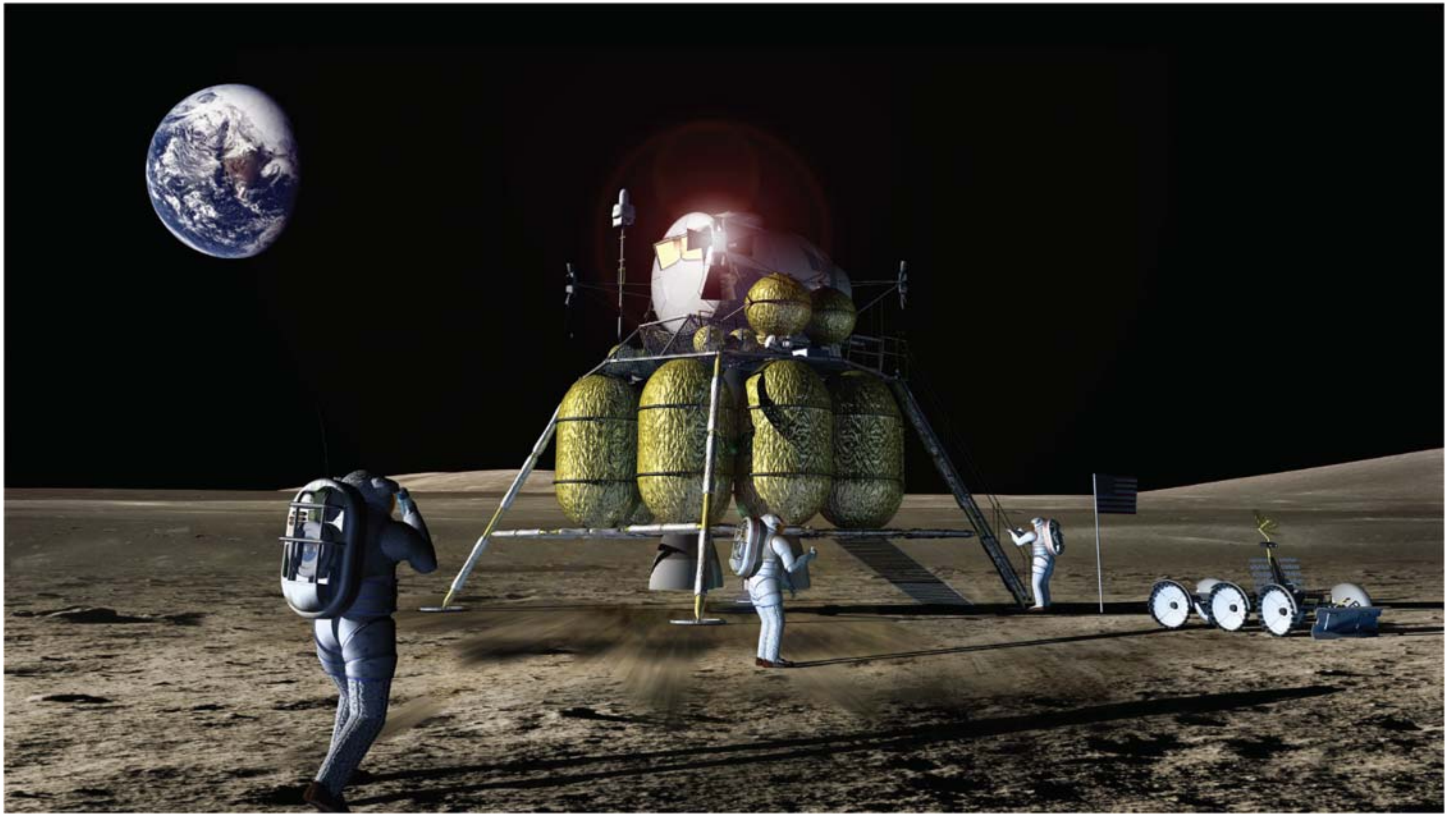


Plate 63 NASA's Vision for Space Exploration marks a new direction for the space agency to return to a long-range program of human exploration of the Moon and eventually Mars within its annual operating budget. Pictured is just one concept for a new generation lunar module and lunar roving vehicle. (NASA)

Plate 64 Rather than a pressurized lunar roving vehicle, the next generation LRV will probably be similar to that pictured here, with the astronauts using the latest Mark series EVA suits that will have increased ease of movement, improved consumable delivery and improved glove design for dexterity and comfort. The LRVs and their crews will be assisted by robotic rovers that can be directed using voice command and which will have autonomous obstacle avoidance. (NASA)

Printing: Mercedes-Druck, Berlin
Binding: Stein + Lehmann, Berlin